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The effect of rheological properties on sludge dewatering in belt filter press

by

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Declaration

I, Buyisile Kholisa, hereby declare that this research dissertation is my own unaided work. It is being submitted for the MEng Degree at the Cape Peninsula University of Technology. It has not been submitted before for any degree or examination in any other University. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

17th of February 2017

Signed **Date**

Abstract

Polymers used as flocculants in the secondary sludge dewatering process are one of the most expensive inputs in these plants. The disadvantage is that these polymers cannot be recycled. Currently, controlling of polymer dosing rate is done by trial and error method. It has been shown that huge savings can be made by optimising the polymer dosing using rheological properties. It is not an easy task to optimise this process because of changing sludge characteristics on a daily, seasonal and annual basis. To try and optimise polymer dosing and polymer concentration, the variation in rheological properties needs to be understood first. The correlation between the process parameters and the rheological properties needs to be determined. There is currently no database of rheological properties of secondary wastewater sludge feeding belt filter presses available.

To address these issues, a 12 week assessment of the rheological properties of the sludge feed to the belt filter press before and after conditioning in four wastewater treatment plants in Cape Town was conducted. The rheological properties were determined using an MCR-51 rheometer with parallel plate geometry under controlled temperature. After concluding the assessment, a 3-level Box-Behnken factorial trial was conducted at Plant K wastewater treatment plant to statistically analyse the correlation and/or interactions between the process parameters (sludge feed flow rate, polymer dosing concentration, polymer dosing rate and belt press speed) and the rheological properties of the sludge to optimise the plant performance.

It was shown that the yield stress values for both unconditioned and conditioned sludges for WWTPs without thickeners were varying over the twelve weeks experimentation. However, for Plant K, the yield stresses for the feed sludge were consistent, while conditioned sludge at 100 cm, 200 cm and 300 cm from the start of belt filter press showed a large variation. This variation was only dependent on solids concentration as delivered by the belt filter press at specific operating parameters.

The relationship between belt filter press operating parameters and yield stress, viscosity, filtrate suspended solids and solids capture was each described by a quadratic function. An interaction effect between operating parameters existed which indicated that the responses do not only depend on one parameter but a joint effect of parameters. The sludge cake solids remained constant over the range of operational parameters tested.

It was also shown that the relationships between the yield stress and viscosity at 100 cm with filtrate suspended solids and solids capture can be described by a polynomial function.

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Dedication

I wish to dedicate this thesis to my mother Ntombizandile Kholisa, and my lovely daughter Analo for their patience and support.

To my family and close friends for their encouragement and support.

To all those having difficult time with their studies

"One of the most common causes of failure is the habit of quitting when one is overtaken by temporary defeat." **R.U Darby**

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Glossary - Terms and Concepts

Anionic: a negatively charged ion especially the ion that migrates to an anode in electrolysis

Cationic: an ion or group of ions having a positive charge and characteristically moving toward the negative electrode in electrolysis

Charge Density: Amount of charged units along polymer chain usually expressed as a percentage.

Dilatant: is a material that tends to become more viscous or solid when affected by an outside force or agitation.

Fluid: a substance whose molecules flow freely, so that it has no fixed shape and little resistance to outside stress, e.g. a liquid or gas.

Molecular weight: is the number of monomer units that are between 1.5 to 30 million amu.

Physico-chemical: is an occurrence that is dependent on or produced by the joint action of physical and chemical agencies.

Polymer: a very large organic molecule that is made of a chain of monomer units possessing a positive or negative surface charge.

Rheometry: the experimental techniques used to determine the rheological properties of materials that are the quantitative and qualitative relationships between deformations and stresses and their derivatives.

Shear thinning: is an effect where a fluid's viscosity which is a measure of a fluid's resistance to flow decreases with an increasing rate of shear strain.

Solids capture: is the percentage of solids recovered from the feed solids.

Viscosity: a measure of the resistance of a substance to motion under an applied force

Yield Stress: is defined as the stress required for initiating flow and is often higher in value.

List of Abbreviations

ADS – Anaerobically digested sludge
AIC – Akaike information criterion
ANOVA – Analysis of variance
AS – Activated sludge
BBD – Box-Behnken Design
BFP – Belt filter press
BOD – Biochemical oxygen demand
CSC – cake solids concentration
CST – Capillary suction time
CSTR – Continuous stirred tank reactor
CV – Coefficient of variation
DAF – Dissolved air flotation
DF – Degree of freedom
DS – Dry solids
EPS – Extracellular polymeric substances
FSS – Filtrate suspended solids
MBR – Membrane bioreactor
MS – Mean of square
PST – Primary settling tank
rHA – Reduced hysteresis area
RMSE – Root mean squared error
SC – Solids capture
SD – Standard deviation
SRF – Specific resistance to filtration
SS – Suspended solids
SST – Secondary settling tank
TS – Total solids
TSS – Total suspended solids
VS – Volatile solids
WAS – Waste activated sludge
WTR – Water treatment residuals
WWTP – Wastewater treatment plant

List of Symbols

Symbol	Description	Unit
A	filtration area	m^2
A_s	surface area	m^2
b	slope coefficient of filtrate ration (t/V) versus V	s/m^6
C	empirical constant	-
D_b	bob diameter	mm
D_c	cup diameter	mm
D_S	solid content of sludge sample	kg/m^3
D_v	vane diameter	mm
E_a	activation energy	$J.mol^{-1}$
F	force	N
H	vane height	mm
k	consistency index	$Pa.s^{-n}$
L_b	bob length	mm
$L_{sludge0}$	initial width of the sludge on the belt	m
m_0	specific mass loading of the sludge on the belt	kgm^{-2}
n	flow behaviour index	-
Q_0	input mass flow rate of sludge	kgs^{-1}
R	universal gas constant	$J.K^{-1}.mol^{-1}$
s_b	belt speed	ms^{-1}
T	absolute temperature	K
t	time	s
V	volume of filtrate	m^3
$\dot{\gamma}$	shear rate	s^{-1}
ΔP	pressure drop across the filter cake	N/m^2
μ	dynamic viscosity	kg/m/s
μ_0	solvent viscosity	Pa.s
$\mu_{100\ cm}$	sludge viscosity at 100 cm	Pa.s
μ_∞	limiting viscosity	Pa.s

μ_c	viscosity at infinite shear rate	Pa.s
μ_p	plastic viscosity	Pa.s
μ_s	suspension viscosity	Pa.s
τ	shear stress	Pa
τ_0	yield stress	Pa
$\tau_{100\ \mathrm{cm}}$	sludge yield stress at 100 cm	Pa
$\emptyset$	volume fraction of the suspension occupied by particles	-

Chapter 1 Introduction

1.1 Background

Wastewater treatment plants (WWTPs) are striving to attain a sustainable sludge management strategy due to the legal banning of conventional sludge disposal methods such as a landfill. However, the increase of water consumption together with the rapid growth of urban populations has resulted in the production of increasing volumes of sewage sludge (Eshtiaghi *et al*., 2013). This increase in sludge sewage volume is putting immense pressure on WWTPs; the large amount of sludge that must be treated and disposed of causes challenges due to regulatory, economic and environmental factors (Djafari *et al*., 2013). Existing municipal wastewater treatment facilities are reaching capacity and require expansion and upgrades to handle the additional load that is anticipated in the future.

The cost of sludge treatment comprises about half of the cost of wastewater treatment (Segalen *et al*., 2015), and the costs continue to increase as new treatment plants are being built and the present ones are being expanded and improved to accommodate the increasing population and tighter regulations. One of the important operations in sewage treatment plants is the dewatering process (Saveyn *et al*., 2008), which is prone to breakdowns and failures (Krylow & Fryzlewicz-Kozak, 2007).

There are several available technologies for sludge dewatering of which the belt filter press (BFP) is widely used due to its relatively low energy consumption (Feng *et al*., 2014). It is very difficult or even impossible to dewater sludge using a belt filter press without pre-treatment; due to the nature of municipal sludge which contains colloidal particles with a substantial number of inorganic and microorganism particles (Feng *et al*., 2014). It is therefore required to pre-treat the sludge before dewatering. Polymers used as flocculants are one of the most expensive inputs in these plants. The disadvantage is that these polymers cannot be recycled. Currently, controlling of polymer dosing rate is done by trial and error method. Dental and co-workers (2000) and Ormeci (2007), have shown that huge savings can be made by optimising the polymer dosing based on the rheological behaviour that affects dewaterability. However, they simply related the area under the torque curve, obtained from the Floccky-tester rheometer, to optimum flocculation, without relating the torque curves to rheological parameters such as yield stress or viscosity. Sewage sludge can be characterised by the Bingham model which contains a yield stress and Bingham viscosity. Some researchers correlated the yield stress and Bingham viscosity to sludge concentration (Seyssiecq *et al*., 2003; Eshtiaghi *et al*., 2013; Wolny *et al*., 2008; Markis *et al*., 2014; Li *et al*., 2012), while others correlated viscosity to flocculation concentration (Bache & Papavasilopoulos, 2000; Tixier *et al*., 2003). It is of great importance to optimise the process by improving its performance, reducing operating costs, minimising environmental impacts and attaining accurate predictions of critical process parameters (Segalen *et al*., 2015). This task is not an easy one because the sludge characteristics could change on a daily, seasonal and annual basis which affects process optimisation, but the extent of these changes are not known.

1.2 Research problem

There is currently no database available on how the rheological properties of secondary wastewater sludge feeding belt filter presses vary. The relationship between sludge rheological properties and belt filter press operating parameters has not been established for sludge dewatering processes.

1.3 Research questions

How do the rheological properties of the secondary sludges from four wastewater treatment plants in Cape Town vary with time?
What is the relationship between the sludge rheological properties and belt filter press operating parameters and the performance measures of the belt filter press?

1.4 Aims and objectives

The aim of this research is to provide a relationship between sludge rheological properties and belt filter press operating parameters that can be used to optimise a belt filter press performance.

The research objectives are:

- To rheologically characterise secondary sludge feeding belt filter presses at four Cape Town wastewater treatment plants to determine the variability.
- To determine the relationship between the sludge rheological properties and belt filter press operating parameters and the performance measures of the belt filter press.

1.5 Significance of this research

Understanding the correlation between the sludge rheological properties and the process parameters may lead to effective plant optimisation and better control of the polymer usage for wastewater treatment plants which could possibly result in cost savings.

1.6 Delineation of the study

Time-dependent properties of the sludge was not measured as these usually diminishes at higher shear rates as was tested in this work. This study was restricted to four wastewater treatment plants around Cape Town. Yield stress and viscosity were the rheological properties of interest in this thesis. Only secondary sludge feeding the belt filter presses was considered.

1.7 Structure of the thesis

Chapter 1 gives the introduction and background to this study. The research problem and research question are highlighted. The aims and objectives of the research are explained and also the significance of this study is discussed.
Chapter 2 gives a comprehensive literature review related to the research.
Chapter 3 describes the research methodology. The first part was to understand the variability of rheological properties of the secondary sludge that feeds the belt filter press before polymer addition and also after it has been added. The second part describes the optimisation study using

a Box-Behnken design in order to study the interaction between the process parameters and the rheological properties and also to determine their effect on the performance of the belt filter press, especially on the final sludge cake.

Chapter 4 gives the results and the discussions pertaining to the determination and the variability of different rheological properties used to characterise the secondary sludge under investigation. The effect of the solids concentration on the rheological properties was evaluated and also the effect of the process parameters on the rheological properties.

Chapter 5 gives the results and the discussions pertaining to the factorial trial. The relationship between rheological properties and belt press performance parameters were evaluated and also the effect of the process parameters on the rheological properties. The effect of process parameters on the rheological properties was also investigated.

Chapter 6 Conclusion related to the observation of the variability in rheological properties as well as in the factorial trial are presented. Relevant recommendations are suggested for further research and the contributions of this study are presented.

Chapter 2 Literature review and theory

2.1 Introduction

This chapter presents a general overview of wastewater treatment plants (WWTP), sources of sludge and a review of the literature on sludge dewatering methods. However, the focus is on a belt filter press as one of the sludge dewatering methods. The methods of evaluating sludge dewaterability and ways of determining belt filter press performance have also been assessed. A review of various types of chemicals used for sludge conditioning has also been conducted. The literature of fluid behaviour and rheology of suspensions have been reviewed. Rheological characterisation methods and rheometry for non-Newtonian fluids have also been assessed.

2.2 Purpose of wastewater treatment plant

Domestic wastewater collected by municipalities must eventually be returned to receiving waters, to the land or be re-used. Modern municipal WWTPs have sequential treatment processes that, when appropriately operated, achieve the desired results. These treatment processes are grouped into primary, secondary and tertiary treatment as shown in Figure 2.1. Wastewater consists of large amounts of organic and inorganic substances, pathogens, and microorganisms. Therefore, the main purpose of WWTPs is to reduce the amount of these contaminants to tolerably low concentrations, hence preventing harmful effects to the public health and the natural environment.

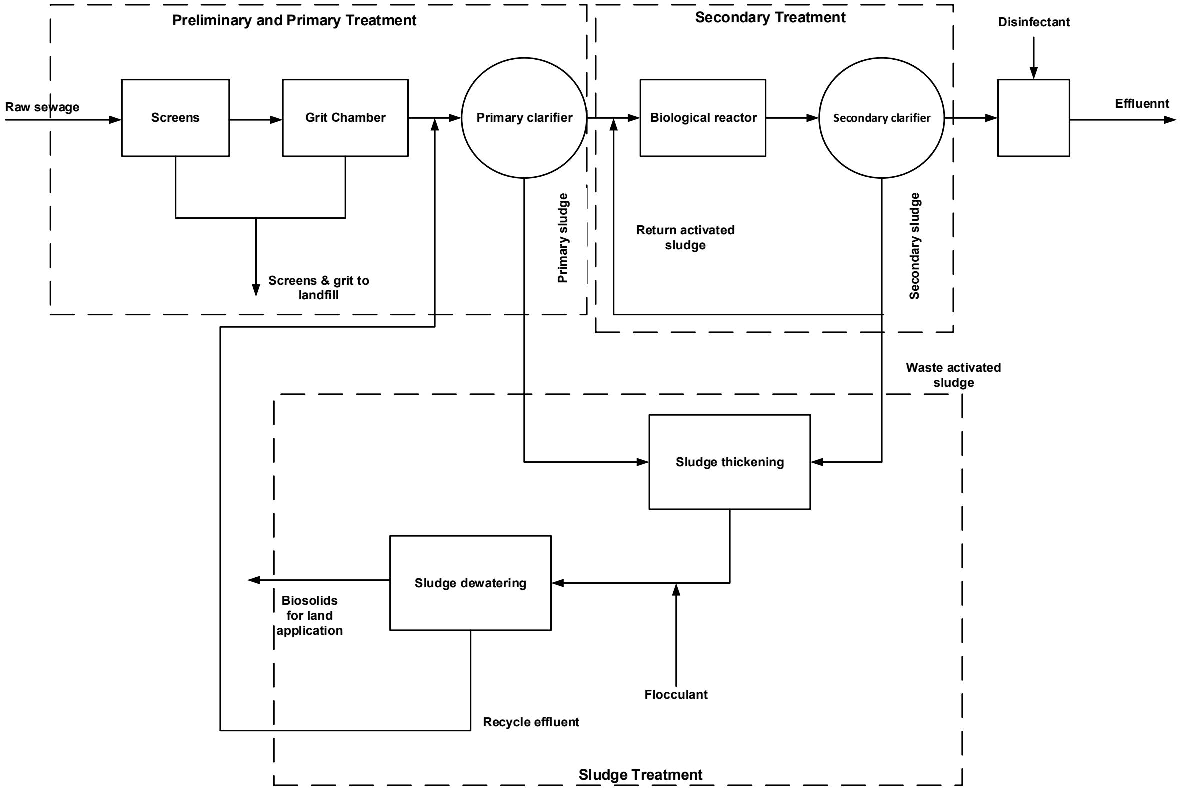


Figure 2.1: Overview of municipal wastewater treatment plant

2.2.1 Primary treatment

Primary treatment is usually the initial step of treatment in a WWTP. Normally bar screens and grit collectors are physical units which are used in the primary treatment; they are designed to remove floating matter like rags, sticks or any large objects and these residues are not handled as sludge because they are likely to damage pumping system (Tchobanoglous *et al*., 2003). From here, the wastewater consists of settleable solids which are sent to a primary settling tank (PST) to create quiescent conditions in order to promote gravitational settlement of the matter. Whatever residual is collected in a PST is known as primary sludge (Masters & Ela, 2008; and Spellman, 2008). Primary sludge is also known as raw sludge simply because it has not gone through biodegradation (Spellman, 2008). The total solids concentration in raw sludge can vary between 2% and 7% by weight (Turovoskiy & Mathai, 2006). This raw sludge is highly odoriferous as it consists of solid substances that are recognisable which make it aesthetically unappealing, and dangerous (Saveyn, 2005). The solids that are not withdrawn from the PST are transported out of the primary treatment unit. These solids have the properties of a colloid and therefore, are called colloidal suspended solids (Spellman, 2008).

2.2.2 Secondary treatment

After a significant amount of solids have been removed from the wastewater, it still contains suspended solids (SS) and a high biochemical oxygen demand (BOD) that can contaminate receiving watercourses. Secondary treatment directly supersedes primary treatment and is intended to remove the SS and BOD. The colloidal suspended solids are converted into more settleable solids so that they can be separated from the wastewater in the secondary treatment process (Spellman, 2008). The secondary treatment, also called activated sludge process, typically involves biological treatment to remove biodegradable organic matter, suspended solids and nutrients using a secondary settling tank (SST) and a biological tank. In the biological tank, an active biomass is combined with wastewater. The active biomass, converts a portion of organic matter in the water into suspended solids, thus decreasing the oxygen demand (Tchobanoglous *et al*., 2003). The biological tank is aerated to ensure that the sludge is in suspension and to provide the microorganisms with oxygen for the conversion of the organic matter. From the biological tank, the sludge is sent to the SST to allow gravitational separation to take place in order to produce a clean effluent. The settleable solids are collected at the bottom and is called secondary sludge. A fraction of the sludge is recycled to the biological tank and the rest is removed as sludge waste.

2.2.3 Variability of sludge characteristics in wastewater treatment plants

Characteristics of municipal wastewater vary from one municipality to another based on the unique mix of domestic, commercial and industrial users and also due to use of different treatment methods the sludge produced vary in quantity and characteristics from one treatment plant to another (Turovovskiy & Mathai, 2006). Leitao *et al*. (2006) affirms that operational and environmental variations are occurring and will always have an effect on wastewater treatment systems.

Krzeminski *et al*. (2012) assessed the seasonal fluctuations of a full-scale membrane bioreactor treating a municipal wastewater. In their research, they assessed the seasonal variability of influent total solids of the activated sludge and other parameters in different seasons of the year from November 2010 to August 2011. The results showed that the solids concentration were high during the summer period and low during winter as shown in Figure 2.2. Also when looking at the overall solids variation, there was about ±14% variability when comparing the standard deviation to the mean.

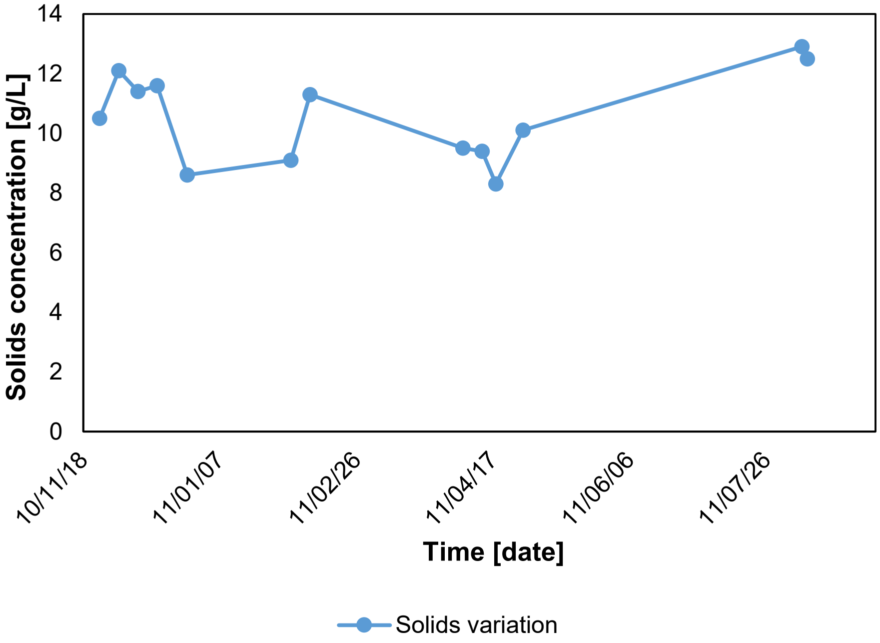


Figure 2.2: Variation of solids concentration for a municipal membrane bioreactor plant (Krzeminski *et al*., 2012)

Tixier *et al*. (2003) pointed out that for a constant solids concentration, variations in sludge viscosity from different plants were observed in the aerobic digestion process.

2.3 Sludge conditioning

Prior to dewatering, sludge is conditioned and conditioning biosolids properly is an essential step in any dewatering process. It is conducted to improve the efficiency of the solid–liquid separation process employed for dewatering. Also it is very difficult or even impossible to dewater sludge using a belt filter press without sludge conditioning process. Sludge conditioning is a process of preparing for the dewatering step by treating sludge suspensions with chemicals or other ways to improve dewatering properties of the sludge. Therefore this section presents the chemicals or conditioning agents that are used in WWTPs.

2.3.1 Inorganic chemicals

Ferric chloride and lime are commonly used inorganic chemicals, although ferrous sulphate and alum are also used (Qasim, 1998). When ferric chloride is added to water through hydrolyses soluble iron complexes that are positively charged are formed. The iron complexes then react with the negatively charged sludge suspended solids to form floc aggregates. Hydroxide $[OH]^-$ ions that cause flocculation are produced when Ferric chloride reacts with the bicarbonate $[HCO_3]^-$ ions that are present in the sludge (Qasim, 1998).

Even though conditioning using ferric salts without any additives will effectively modify the sludge, the enhancement in dewaterability is insufficient for most purposes. This is attributed to the properties of the iron hydroxide such as high compressibility, amorphous and hydrophilic; it contributes to a sludge that is barely dewaterable (Saveyn, 2005). Therefore, the ferric salts are normally used in combination with lime since it offers pH control, odour reduction, and disinfection (Qasim, 1998). Iron-lime conditioning produces a sludge with good permeability and with less incorporated water when pressure is used (Saveyn, 2005). The utilisation of lime and ferric chloride, however, can increase the original dry weight of sludge by 20% to 40% (Qasim, 1998 and Saveyn, 2005). Although inorganic chemicals are reasonably economical and the selection process is quick and easy, the main drawback of using it is the fact that it increases dry solids by up to 20 to 40% (Saveyn, 2005).

Ferric chloride and lime are usually used in sludge dewatering process such as pressure filters and vacuum filters. According to Wang et al. (2007), ferric chloride is typically dosed at a dosing rate of 20 kg/t to 62 kg/t of dry solids in the sludge feed, irrespective of lime is used or not. Lime dosage is typically in the range of 75 kg/t to 277 kg/t. Table 2.1 lists typical dosing requirements for ferric chloride and lime for various municipal wastewater sludges.

Table 2.1: Typical dosing requirements of ferric chloride and lime for municipal wastewater sludges (adapted from Wang et al. (2007))

Type of sludge	Vacuum filter (kg/t)		Pressure filter (kg/t)	
	$FeCl_3$	CaO	$FeCl_3$	CaO
Raw				
Primary	20 - 40	80 - 100	40 -120	10 - 140
WAS	60 - 100	0 - 160	70 - 100	200 - 250
Primary + WAS	25 - 40	120 - 150	-	-
Aerobically digested				
Primary	30 - 50	100 - 130	-	-
Primary + WAS	30 - 60	150 - 210	-	-

2.3.2 Organic chemicals

Organic polymers (polyelectrolytes) are used extensively in wastewater treatment and sludge conditioning. The polymers that are used, are synthetic organic polymers with high molecular weight, produced by the polymerisation of homopolymer or copolymer kinds of monomer compounds (Freese *et al*., 2004). These materials vary significantly in chemical composition and functional effectiveness (Qasim, 1998). The electronic charge, solubility, and molecular weight can supply valuable data with regards to the effectiveness and the harmfulness of a certain polymer (Freese *et al*., 2004).

Polymers dissociate upon addition to water into negatively and positively charged species and are customarily categorised. Polymers holding an overall positive charge are called cationic, and those that have an overall negative charge are anionic. In some cases, these polymers are nonionic being neutral and amphoteric having together negative and positive charges (Freese *et al*., 2004). The higher the charge of a polymer, the higher solubility and therefore the more bioavailable to aquatic organisms (Freese *et al*., 2004). Cationic synthetic polymers are the dominating type of organic chemicals used in sludge conditioning (Saveyn, 2005). Polymers are categorised by active solids level (2 - 95%), charge density percentage (10 - 100%), and molecular weight (0.5 - 18 million monomer units) (Qasim, 1998). Solutions of different viscosity are produced when organic polymers are dissolved in water, depending on the polymer concentration. Saveyn (2005) states that even though organic polymers are considerably cheaper to use and being added approximately at 1% of the dry matter content, the high variation of available polymers calls for extensive examination to determine the most effective and efficient product.

Cationic polyacrylamide (CPAM), is the most widely accepted organic synthetic flocculant in sludge dewatering, is known to have high reduction in turbidity treatment (Ho *et al*., 2010). Polymer conditioning is the common practice for sludge dewatering with centrifuges and belt filter presses. Polymer dosing varies from 1 to 10 kg/t of dry solids, depending on the type and dewaterability of sludge and also the dewatering equipment (Turovskiy & Mathai, 2006). Table 2.2 lists typical dosing requirements for polymers for various municipal wastewater sludges and dewatering methods. Turovskiy and Mathai (2006), state that increasing the polymer dosing beyond the optimum levels worsens the dewaterability of sludge.

Table 2.2: Typical polymer dosages for various types of sludge and dewatering equipment (Turovskiy & Mathai, 2006)

Dewatering method	Type of sludge	Polymer dosage (kg/t dry solids)
Belt filter press	Raw primary	1.2 – 3.3
	Raw WAS	2.6 – 6.5
	Raw (primary + WAS)	3 – 6
	Anaerobically digested primary	2 – 4
	Anaerobically digested (primary+ WAS)	3 – 8
Solid bow centrifuge	Raw primary	0.5 – 2.3
	Raw WAS	3 – 8
	Raw (primary + WAS)	2 – 6
	Anaerobically digested (primary + WAS)	2.5 – 8.0
	Anaerobically digested primary	3.6 – 9.0
	Anaerobically digested WAS	5.0 – 9.7
Vacuum filter	Raw primary	2 – 5
	Raw (primary + WAS)	4 – 7
	Anaerobically digested (primary+ WAS)	4.4 – 8.7
	Anaerobically digested primary	3.6 – 9.0
Recessed plate filter press	Raw (primary + WAS)	2 – 7

2.4 Sludge dewatering process

Sludge dewatering is usually the last step for municipal WWTPs and is the process of removal of water from sludge. After wastewater treatment (WWT), the remaining sludge still contains a very large amount of water that can be recovered via sludge dewatering. The excess or waste sludge produced in biological treatment is sent to the dewatering process for further treatment in order to reduce disposal costs, environmental impact, and to meet regulations. The dewatering processes that are usually utilised comprise of natural processes like sand drying beds and drying lagoons, mechanical processes like belt filter presses, centrifuges, and pressure filter presses (Spellman, 2008). For this study, mechanical processes and more specifically sludge dewatered by belt filter presses are presented in detail.

2.4.1 Centrifuges

In the solid-bowl machine, the sludge is fed at a constant flow rate into the conically shaped rotating bowl, which aids to lift the solids out of the sludge permitting it to dry on an inclined surface before being released. The dilute stream is reverted to the WWT system known as filtrate, whereas the sludge cake is released from the bowl by a screw feeder into a hopper or onto a conveyor belt. The sludge cake contains approximately 70% to 80% moisture or alternatively (30% to 20% dry solids) (Tchobanoglous *et al.*, 2003).

2.4.2 Pressure filter presses

The pressure filter press is a non-continuous or batch process (Tuan, 2011). The pressure equipment used to dewater sludge are membrane plate presses, recessed plate presses, frame and plate filter presses (Wakeman, 2007). The membrane plate presses have the ability to utilise the compressible nature of the sludge, and that makes them generally valuable for sludge dewatering purposes (Wakeman, 2007). According to Tuan (2011) and Wakeman (2007), a normal filtration step for dewatering is: firstly feeding the sludge; followed by squeezing the cake through inflating the membranes; thirdly air is blown through the cake; lastly the core is washed and/or blown. The applied pressure is normally in the range of 22,6x10^4 N/m^2 to 155x10^4 N/m^2 and is kept for about 60 to 120 minutes in the fixed-volume recessed plate filter press in contrast to 1,380 N/m^2 to 2,070 MN/m^2 and 15 to 30 minutes in the diaphragm press (Tuan, 2011). Dewatered cake differs in solids concentration from that of moist soil from 20% to 40% solids to custard (12-15% solids) (Wang *et al.*, 2007).

2.4.3 Belt filter presses

Most biosolids produced at municipal WWTPs are dewatered using belt filter presses (BFP). BFPs are characterised by two continuous, tensioned filter cloths (Wakeman, 2007). Biosolids are sandwiched between the two tensioned porous belts that pass over and under rollers of various diameters and as the roller diameters decrease along the belt press a higher pressure is generated (Wang *et al*., 2007). According to Tuan (2011), there are three stages involved in a BFP as shown by Figure 2.3.

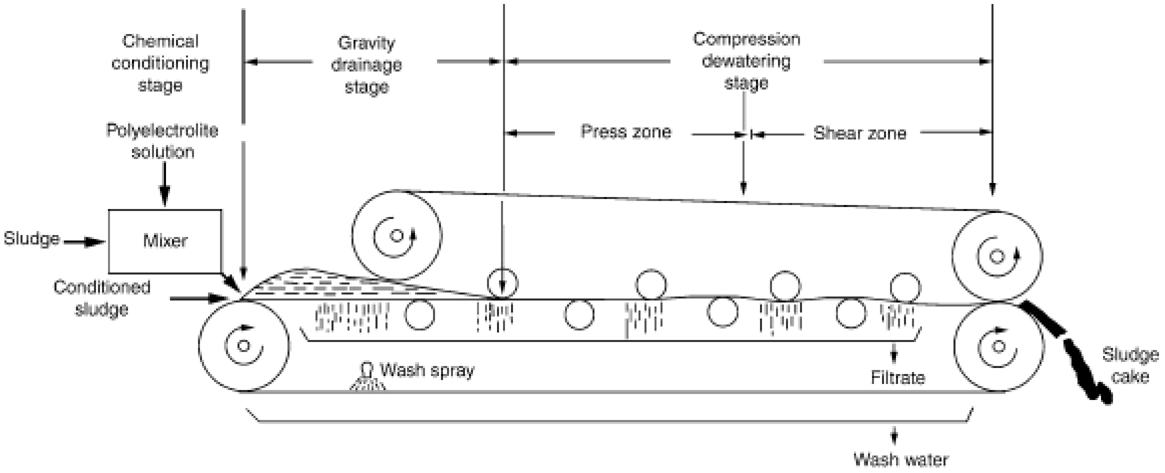


Figure 2.3: Three stages of a belt press (Wang *et al*., 2007)

In the initial stage, flocculated sludge is fed to the lower cloth (belt) and the dewatering is under gravity. In the second stage, the sludge is squeezed by low-pressure application between porous cloth filter belts. The low-pressure stage is followed by the high-pressure stage when the belts pass through a series of rollers. Figure 2.4 gives an overview of a BFP.

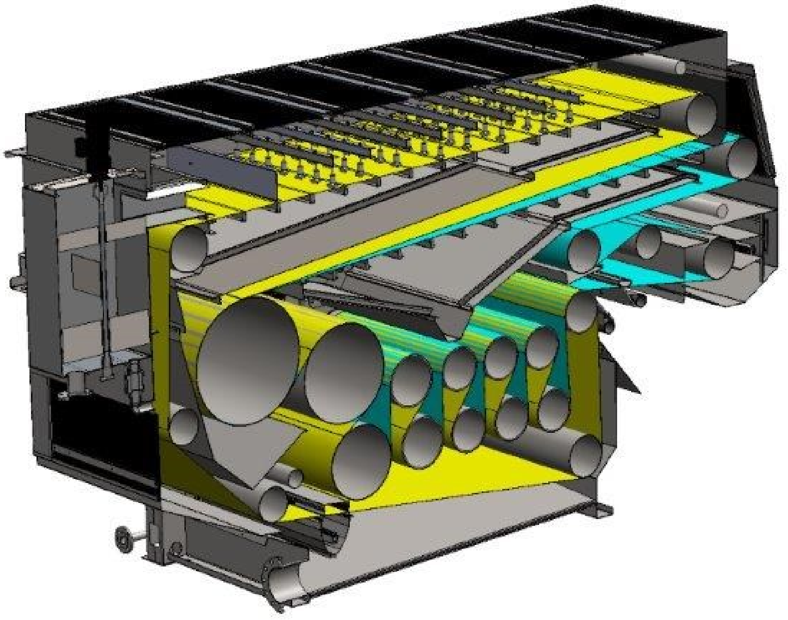


Figure 2.4: Typical belt filter press (Potsdam wastewater works operating manual)

Normally, the sludge fed to a BFP varies from 99% to 96% water (1-4% feed solids) and produces a final cake product about 88% to 65% moisture or 12% to 35% cake solids. The performance of the belt press depends mainly on the type of the solids being treated (Wang *et al*., 2007).

2.4.4 Comparison of mechanical dewatering systems

A comparison of different mechanical devices for dewatering various types of sludge and biosolids is shown in Table 2.3.

Table 2.3: A comparison of mechanical devices for dewatering various types of sludge and biosolids (adapted from Tchobanoglous *et al*., 2003).

Dewatering method	Advantages	Disadvantages
Belt filter press	Minimal effort required for system shutdown. Low energy requirements. Not complicated mechanically and is easier to sustain. Moderately low operating and capital costs.	High sensitivity to sludge characteristics of the feed stream. Automatic operation. Grinder is required for sludge feed stream. High odor potential.
Solid-bowl centrifuge	Good odour containment. Clean appearance. Produces a relatively dry sludge cake. High installed capacity to building area ratio. High capacity-to-capital cost ratio. Fast start-up and shutdown capabilities.	Grit removal is required and perhaps a sludge grinder in the sludge feed stream. High maintenance problem due to scroll wear. Produces filtrate with fairly high suspended solids content. Skilled maintenance personnel required.
Pressure filter press	Filtrate with low suspended solids Highest cake solids concentration	Special support structure requirements Non-continuous operation High labour cost High equipment cost Skilled maintenance personnel required Equipment requires large floor area Produces large amount of solids volume due to large chemical addition

2.5 Evaluation of sludge dewaterability

Common parameters used to evaluate sludge dewatering properties include capillary suction time (CST) and specific resistance to filtration (SRF).

2.5.1 Capillary suction time

The CST test includes measuring the time to move a volume of filtrate over a specified distance as a result of the capillary suction pressure of dry filter paper measured in seconds. The CST test provides information regarding the ease of separating the water portion from the solids portion of sludge (Salazar & Moreno, 2013). Figure 2.5 shows the CST device used in wastewater treatment.

Figure 2.5: Capillary suction time device (model 319 Multi-purpose CST) adapted from (Scholz, 2005)

2.5.2 Specific resistance to filtration

The SRF test consists of placing sludge samples in a Buchner funnel with a paper support filter and applying a vacuum. The funnel is connected to a graduated cylinder and the amount of filtrate is measured as a function of time. The SRF parameter is reported in m/kg (Tuan, 2011) and it can be calculated as follows:

$$\mathrm{SRF} = \frac{2\mathrm{x}10^{12}\ \mathrm{A}^2\Delta\mathrm{Pb}}{\mu\mathrm{D_s}}$$ Equation 2.1

Where: ΔP (N/m^2) is the pressure drop across the filter cake, A (m^2) is filtration area, μ (kg/m.s^{-1}) is dynamic viscosity, D_S (kg/m^3) is the solid content of sludge sample. The coefficient b (s/m^6) is measured as the slope of the curve obtained by plotting the time of filtration to volume of filtrate ration (t/V) versus V.

2.6 Belt filter press (BFP) performance

BFP efficiency is measured by three criteria: the dry solids content of the dewatered sludge, percentage of solids recovered and lateral sludge migration on the belt (Olivier & Vaxelaire, 2005). Only the findings of a few studies have been published on the impact of operating parameters on the dry solids content of dewatered sludge and these studies have been carried out on industrial machines (Olivier & Vaxelaire, 2005).

Olivier and Vaxelaire (2005) studied the impact of the number of pressing cycles and they observed that the sludge was essentially dewatered after three cycles with 97% to 99% of the filtrate removed. They studied the impact of the belt speed on the dry solids content and their results showed that a decrease in belt speed significantly increases the dry solids content of the dewatered sludge. The sludge was also easier to remove from the belt after pressing. Their results also showed that the decrease in belt speed brought a noticeable reduction in lateral sludge migration and considerably increased filtrate quality. Table 2.4 gives a summary of some studies that have been carried out on the impact of operating parameters on the efficiency of BFP (Olivier & Vaxelaire, 2005).

Table 2.4: Summary of studies that carried out on the impact of operating parameters on the efficiency of BFP (Olivier & Vaxelaire, 2005).

Parameter	Dry solids content of dewatered sludge	Percentage recovery of solids	Lateral migration of sludge	Nature of the sludge	Reference
Increased belt speed	Decrease	No data available	No data available	Mixed sludge	Haworth, 1973; Inujuma *et al*., 1986; Tokunaga *et al*., 1983
	Decrease	No data available	No data available	Digested sludge	Haworth, 1973
	Decrease	No data available	No data available	Leather-making industry	Minyuan, 1991
	No impact	No data available	No data available	Not specified	Lecey & Pietila, 1983
	Very slight decrease	Decrease	Increase	Mixed sludge	Lotito *et al*., 1986
Increase of belt tension	Increase	No data available	No data available	Mixed sludge	Haworth, 1973; Inujuma etal., 1986; Tokunaga *et al*., 1983
	Increase	No data available	No data available	Digested sludge	Haworth, 1973
	Increase	Decrease/No impact	No data available	Not specified	Lecey & Pietila, 1983
	Increase		No data available	Alum sludge	Johnson *et al*., 1992
	No data available	Decrease/No impact	No data available	Activated sludge	Graham *et al*., 1998
Increase of input sludge flow rate of sludge	Decrease	Increase	Increase	Mixed	Lotito *et al*., 1986
Increase of initial dry solids content	Increase	No data available	No data available	Mixed sludge	Inujuma etal., 1986
	Increase	Increase	Increase	Mixed sludge	Lotito *et al*., 1986
	Increase	No data available	No data available	Not specified	Lecey & Pietila, 1983

According to Wang (2007), the biosolids input mass flow rate has a substantial negative impact on the overall efficiency of the belt filter press unit. An input mass flow rate that is very high will reduce the performance, in other words, the belt filter press will produce a final sludge cake with high moisture content. Table 2.5 shows a list of indicators that causes poor performance of BFP (Spellman, 2008). The ideal input mass flow rate is the maximum flow rate that the process equipment can be operated at, without a decrease in the preferred efficiency and is a function of belt speed. The correlation between input mass flow rate and belt speed can be shown by the following equation (Olivier & Vaxelaire, 2005):

$$\mathrm{Q_0 = m_0 s_b L_{sludge0}} \qquad \text{Equation 2.2}$$

Where: Q_0 (kgs^{-1}) is the input mass flow rate of sludge, m_0 ($kg.m^{-2}$) is the specific mass loading of the sludge on the belt, s_b ($m.s^{-1}$) is the belt speed and $L_{sludge0}$ (m) is the initial width of the sludge on the belt.

Table 2.5: A list of several indicators for poor performance for BFP, their casual factors and corrective actions (Spellman, 2008).

Symptom	Cause	Corrective action
Belt shifts or seizes.	Irregular sludge spreading. Poor or irregular belt wash.	Regulate feed for even sludge spreading. Regulate and clean belt-washing sprays.
Sludge is dripping from the sides of the belt.	Too much belt tension. Belt too slow. Too much sludge feed rate.	Reduce the tension of the belt. Increase the speed of the belt. Decrease the feed rate of the sludge.
Discharging the filter cake is problematic.	Inappropriate chemical dosage. Sludge characteristics are changing. Incorrect conditioning chemical is chosen. Incorrect application point.	Alter the conditioning chemical. Alter the dosage of the chemical. Alter conditioning chemical Adjust point of application.
Too much moisture found in filter cake	Inappropriate draining time or speed of the belt. Incorrect chemical for conditioning. Inappropriate dosage rate of the chemical. Poor washing of the belt. Incorrect material or weave of the belt.	Alter belt speed. Alter conditioning chemical. Alter chemical dosage. Clean up spraying nozzles and align sprays. Change the belt.
The edges of the belt are damaged too much	Rollers are aligned improperly Inadequate tension of the belt tension. Alignment/tension control system.	Correct roller alignment. Correct belt tension. Rectify alignment and tracking system controls.

2.7 Optimisation of sludge dewatering process

Optimisation of sludge dewatering procedures requires optimisation of polymer conditioning. Wastewater treatment plants continue to use laboratory tests such as CST and SRF to understand sludge behaviour under different conditioning patterns (Scholz, 2005; Peng *et al.*, 2011). However, the obtained information cannot be used to predict the performance of full-scale facilities.

Ormeci (2007) applied the rheological technique to optimising polymer dose and mixing intensity in sludge dewatering using a Floccky Tester, which is a torque rheometer type. In his study, he presented two different techniques that can be used for optimising the polymer dosing and mixing intensity, also for selecting a polymer that performs the best based on rheological data. The first technique is used for sludges before polymer addtion and rheogram peaks are observed after the polymer addition. The second technique is used for sludges after polymer addition and uses the torque-time rheograms. Three different polymer were tested by both these techniques at the lab and full-scale WWTPs. These techniques were able to optimise the polymer dosing and mixing intensity also the polymer consumption was reduced by 50% at the treatment plant. In addition, the results indicated that torque rheology can be used to determine the total shear intensity impose to sludge during full-scale conditioning. Also based on the rheological properties of the sludge the jar-tester shear can be matched to the total shear. The results of this study indicates that well-described rheological properties of sludge offer a reliable tool for the optimisation of dewatering operations and sludge conditioning at wastewater treatment plants.

Salazar *et al*. (2013) also attempted to optimise polymer dosage. Their objective was to define the main parameters that affect the overall dewaterability performance in terms of dried solids (DS) content of the final sludge cake. The trials were conducted at a full-scale WWTP that was using filter presses, NALCO polyacrylamide-based polymer was tested and the dosage was optimised in the range of 7 ml to 8 ml polymer per 100 ml of digested sludge (7% to 8% volume per volume). The best capillary suction time values (CST) were obtained at 8.96 and 9.94 seconds respectively; however, the polymer dosage did not result in any improvements of the DS of the sludge cake.

Johnson *et al*. (1992) conducted a series of tests on a new belt filter press at a filtration plant. The operating parameters such as solids feed, sludge flow rate, polymer dosage, and belt speed and tension were identified as being critical to belt filter press efficiency and optimisation. Each belt press control parameter was tested to determine the optimum range of performance in terms of cake production and cake solids percentage. No correlation could be found, with either production or cake solids percentage.

2.8 Rheology

2.8.1 Introduction

There are numerous definitions of *rheology* available in the literature. However, the most common definition is that rheology is the science of deformation and of matter (Barnes *et al.*, 1989; Macosko, 1994 & Mezger, 2006). Mezger (2006) expanded further stating that rheological experiments do not merely reveal information about the flow behaviour of liquids, but also the deformation behaviour of solids. The relationship here is that a large deformation produced by a shear forces cause many materials to flow. Rheology can be used as a tool to characterise different types of materials from ideal liquids through to ideal solids. Determining rheological properties such as viscosity or yield stress is very important in the managing sewage sludge, for example they are design parameters in transporting, spreading, and storing operations (Lotito *et al.*, 1997 cited in Tixier *et al.*, 2003).

Consider a thin layer of fluid between parallel planes as shown in Figure 2.6 distance dy apart. For steady state conditions, when force F is applied to the upper plane of the surface area (A_s), while the bottom layer is stationary causes a shear stresses to the liquid. The shear stress experienced by the fluid can be expressed be by Equation 2.3:

$$\tau = \frac{F}{A_s} \qquad \text{Equation 2.3}$$

The shear rate determines the velocity gradient or the speed at which the different layers of the liquid are being sheared, defined as Equation 2.4:

$$\dot{\gamma} = -\frac{dV_x}{dy} \qquad \text{Equation 2.4}$$

Sir Isaac Newton established that the shear stress and the shear rate are indirectly proportional when he observed the flow properties of an ideal liquid. The constant of proportionality noted by μ was therefore defined as the viscosity of the material given by Equation 2.5:

$$\tau = \mu.\dot{\gamma} \qquad \text{Equation 2.5}$$

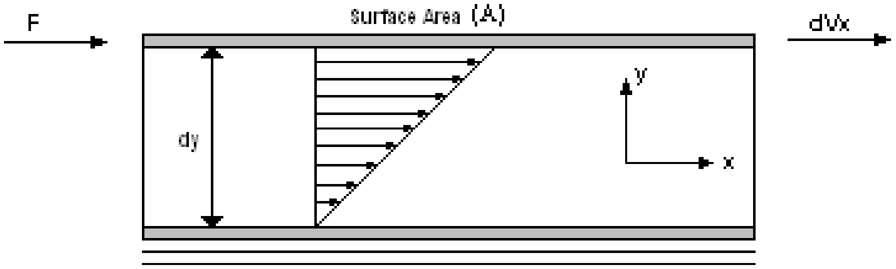


Figure 2.6: Schematic representation of unidirectional shearing flow (Chhabra and Richardson, 2008)

2.8.2 Newtonian fluid flow behaviour

Fluids that comply with Newtown's law of viscosity, are known as Newtonian fluids (Geankoplis, 1993). A Newtonian viscosity is constant for a given fluid, although it generally varies if either the temperature, pressure, or the concentration of a particulate material changes (Seyssiecq *et al*., 2003). For Newtonian fluids, a shear stress – shear rate relationship is always represented by a straight line through the origin of the coordinates (Chhabra & Richardson, 2008). The straight line has different slopes to signify different Newtonian fluids with different viscosities, therefore, the higher the viscosity of a fluid the steeper the slope μ. Figure 2.7 shows the rheograms of different Newtonian fluids. Shear stress versus shear rate graphs are known as rheograms or flow curves. The constant μ completely characterises the flow behaviour of a Newtonian fluid at a fixed temperature and pressure (Chhabra & Richardson, 2008).

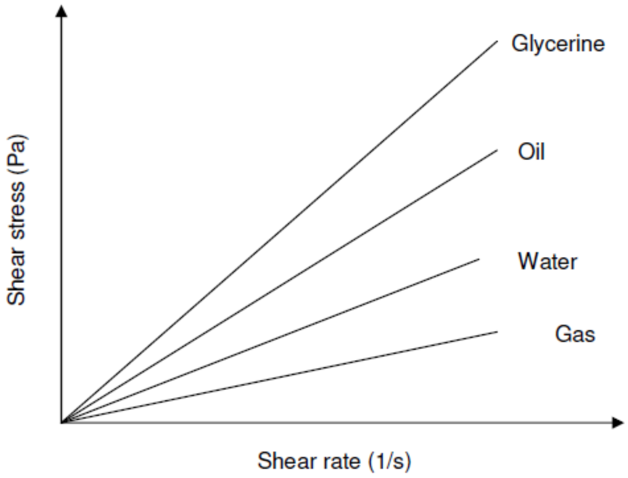


Figure 2.7: Rheogram of different Newtonian fluids (Chhabra & Richardson, 2008).

2.8.3 Non-Newtonian flow behaviour

The behaviour of non-Newtonian fluids is more complex than Newtonian fluids. The shear stress is not directly proportional to the shear rate or the flow curve does not go through the origin for non-Newtonian fluids such as wastewater sludges (Chhabra & Richardson, 2008 and Holland & Bragg, 1995). The term apparent viscosity is used to distinguish this behaviour (Holland & Bragg, 1995). This parameter is an important measure of a physical characteristic of sludge suspensions concerning deformation and flow properties.

Some non-Newtonian fluids start to flow once a certain level of stress is exceeded. Below this critical stress level, a non-Newtonian fluid essentially acts a solid and will continue to do so until the stress reaches the shear force needed to overcome the internal friction of the material. This critical stress is known as yield stress.

Non-Newtonian fluids behave differently to the applied shear stress, for example, their apparent viscosity increases or decreases as the shear rate increases. When apparent viscosity decreases with an increase in the shear rate these fluids are referred to as *shear thinning* or *pseudoplastic* while those experiencing an increase in apparent viscosity are referred to as shear *thickening* or *dilatants*. Those non-Newtonian fluids whose apparent viscosity remains constant with an increase in shear rate are referred to as Bingham plastic fluids. Figure 2.8 illustrates different types of fluid behaviour.

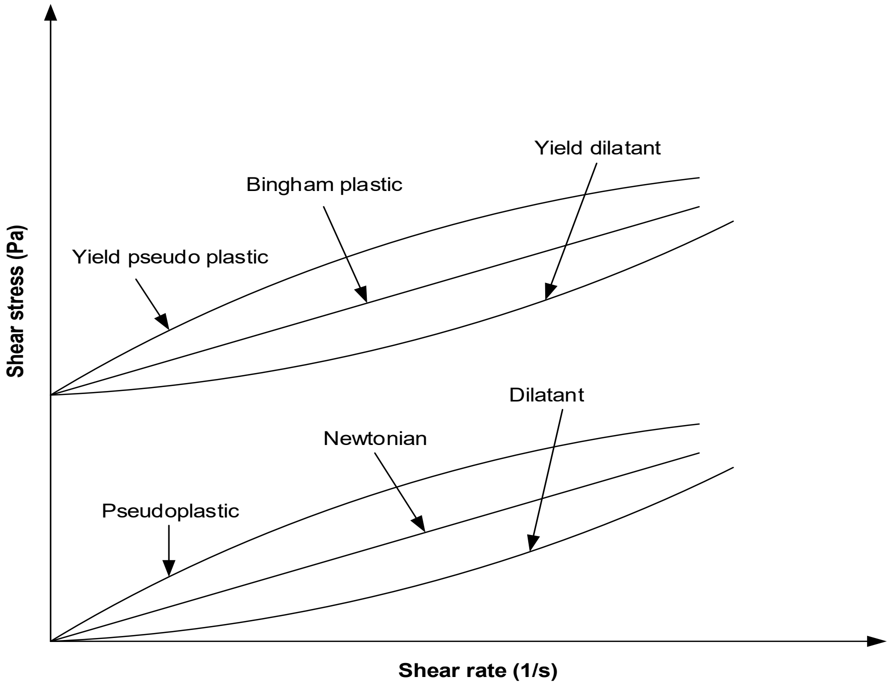


Figure 2.8: Illustrate rheological models used for Newtonian, Dilatant, Bingham plastic (or plastic) and pseudoplastic fluids (Chhabra & Richardson, 2008)

2.8.4 Viscosity of suspension

Thus far, the discussion has been based only on a single homogenous phase. However, two-phase slurries such as activated sludge do not obey Newton's law of viscosity as described by Equation 2.5 (Sanin *et al*., 2002). This is due to the presence of solids that have an effect on the viscosity of the suspension. The relationship between concentration and suspension viscosity is quantified by the Einstein viscosity equation (Equation 2.6) (Bird *et al*., 2002).

$$\mu_s = \mu_0(1 + 2.5\emptyset) \quad \text{Equation 2.6}$$

Where μ_s is the suspension viscosity, μ_0 is the solvent (water) viscosity and $\emptyset$ is the volume fraction of the suspension occupied by particles.

For dilute suspensions, Equation 2.5 can be used since the force of attraction between particles is very weak.

2.8.5 Rheological models

Rheology has been extensively used to characterise sludges and suspensions in wastewater. A number of mathematical models have been developed by researchers all over the world, in order to practically define and analyse material behaviour (Seyssieq *et al.*, 2003). Prominent researchers are cited by Estiaghi *et al*. (2013), confirming that the flow models of simple Power law, Bingham, Herschel-Bulkley, Sisko and Casson have been applied in defining non-Newtonian sludge flow behaviour in steady-state laminar flow. Nonetheless, out of all the previously mentioned flow models, the Power law and Bingham models are mostly used in characterising sludge rheology, their particular application depends on whether the has a yield stress or not. The models have been used to characterise sludge rheology are given in Equation 2.7 to Equation 2.11.

Power- law (Ostwald-de Waele)

$$\tau = \mathrm{k}\dot{\gamma}^{\mathrm{n}} \qquad \text{Equation 2.7}$$

Casson model

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu_{\mathrm{p}}\dot{\gamma}} \qquad \text{Equation 2.8}$$

Bingham plastic model

$$\tau = \tau_0 + \mathrm{k}\dot{\gamma} \qquad \text{Equation 2.9}$$

Herschel-Bulkley model

$$\tau = \tau_0 + \mathrm{k}\dot{\gamma}^{\mathrm{n}} \qquad \text{Equation 2.10}$$

Sisko model

$$\tau = \mu_c\dot{\gamma} + k\dot{\gamma}^n \qquad \text{Equation 2.11}$$

In these models, τ_0 is the yield stress, k is the consistency index, n is the flow behaviour index, μ_p is the plastic viscosity, μ_c is the viscosity at infinite shear rate, τ is the shear stress and $\dot{\gamma}$ is the shear rate.

When looking at these models, it can be noted that the Herschel-Bulkley model becomes the power law model when τ_0 is equal to zero and Bingham model when n the flow behaviour index is equal to one. The consistency index (k) corresponds to the plastic viscosity.

2.8.6 Devices used in rheometry

Rheometry generically implies to the techniques applied in rheology in order to establish the rheological properties of materials. The said rheological properties comprise of the qualitative and quantitative association between deformations and stresses and their derivatives. A variety of rheometry devices are utilised in industry for rheological experimentation. Rheological experimentation is but the first step of receiving the raw data before, subsequent analysis methods of approximation and regression are implemented. Common rheological instruments used within the rheology domain are illustrated in Figure 2.9:

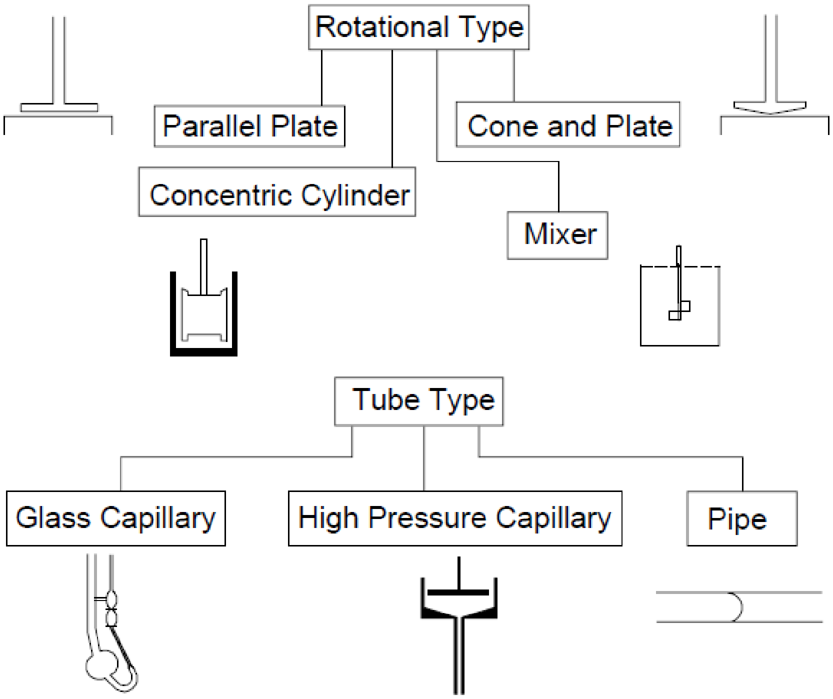


Figure 2.9: Common rheological instruments split into two major groups of rotational and tube type (Steffe, 1996)

Seyssieq *et al*. (2003), in their of state of the art review of rheological characterisation of wastewater treatment sludges, concluded that a rotational rheometer is one type of rheometer mostly used for sludge suspensions, as it takes into account the material's time-dependent properties. Rotational rheometers are also able to characterise rheological properties as a function of temperature and the material's solids concentration. As a measure to enhance the rheological quality of results during experimentation, Seyssieq *et al*. (2003) proposed that one should always conduct rheological tests of concentrated suspensions in the same manner. In addition to the above guideline, they forewarned that, the rough rheological properties of suspensions can never be known, as the thixotropic nature of sludge suspensions hinder the obtainability of true rheological measurements because in most instances the sample has to undergo pre-shearing as a form of preparation.

2.9 Rheological application in wastewater sludge

2.9.1 Introduction

Determining rheological properties, for instance, yield stress or viscosity is important for the optimum management of sewage sludge, for designing considerations in spreading, storing, and transporting operations or designing pumping system requirements (Lotito *et al.*, 1997). Improvement of actual sludge treatment using sludge rheological characteristics has been implemented successfully by Abu-Orf & Dentel (1999), especially in sludge dewatering and conditioning operations (Dentel *et al.*, 2000; Yen *et al.*, 2002). It is important to characterise sludge at different stages of a WWTP since it allows for the prediction and the estimation of sludge behaviour (Abu-Jdayil *et al.*, 2010). Total suspended solids is said to be the most important characteristic affecting sludge rheology (Hasar *et al.*, 2004). It has been found by several authors that, at a weak TSS the Bingham parameters are defined by a linear law (Abu-Jdayil *et al.*, 2009). Markis *et al.* (2014) graphically illustrated changes in the rheological behaviour of sludges that were directly linked to an increase in the concentration of the material. Tixier *et al.* (2003) cited Monteiro (1997) and Slatter (1997) as both acknowledging the influence of TSS on the rheological characteristics of a material. Rheology is, therefore, a useful tool with its versatile utilisation, the sludge hydrodynamic characteristics can be analysed and wastewater process optimisation can be effected for improved results (Seyssieq *et al.*, 2003).

2.9.2 Factors influencing apparent viscosity

2.9.2.1 Solids concentration

This parameter has been an important measure of a physical characteristic of sludge suspension concerning deformation and flow properties. Since sludge is a non-Newtonian fluid, as the viscosity changes with the shear rate or applied stress, the term apparent viscosity is used to describe this behaviour (Estiaghi *et al.*, 2013).

For activated sludge, the viscosity is affected strongly by the particle-particle interaction of the sludge (Djafari *et al.*, 2013). There are other variables that affect the sludge viscosity which are extracellular polymeric substances (EPS), the Total Suspended Solids (TSS), surface charge; the ionic strength of the bulk solution content, temperature and the particle size (Djafari *et al.*, 2013).

Pevere *et al*. (2006) demonstrated that at the same solids concentrations, samples with a smaller particle range will exhibit an increased limit viscosity in the sludge. An analogy linked to this viscosity increase is ascribed to the increase in particle-particle interaction. Pevere *et al*. (2006), concluded that particle-particle interaction is of utmost importance with regards to the quantities it occupies in sludge materials.

Tixier and co-workers (2003) studied the rheological characterisation of activated sludge coming from a laboratory scale plant and also from different aeration tanks using rotational rheometry tests. They were interested in reduced hysteresis area (rHA) and limiting viscosity as their rheological properties. The presence of excess filaments in sludge produces different flow curves at an increasing or decreasing shear rate, therefore these upward and downward flow curves describe the rHa. Limit viscosity corresponds to the viscosity of a fluid at the maximum dispersion of the aggregates under the effect of the shear rate (Bjorn, 2012). They observed that limit viscosity was mainly influenced by the TSS content of the sludge and had an exponential relation. Sanin (2002) also observed an exponential relation when examining the solids concentration effect on apparent viscosity of the activated sludge where an increase in the concentration of the solids increased the apparent viscosity sharply.

2.9.2.2 Temperature

Another significant factor affecting the apparent viscosity of sludge is temperature. Abu-Jdayil *et al*. (2010) observed that an increase in temperature of the sludge caused a decrease in limiting viscosity. This is due to the fact that when a temperature of a liquid is raised, its particles become energised and start moving. The energy produced by the movement is sufficient to break up the forces that hold the particles together, thus, its viscosity is decreased (Darby, 2001). The relationship between the temperature and limiting viscosity can be described by an Arrhenius type equation (Abu-Jdayil *et al*., 2010):

$$\mu_{\infty} = \mathrm{C}e^{\frac{\mathrm{E_a}}{\mathrm{RT}}} \qquad \text{Equation 2.12}$$

Where μ_{∞} is the limiting viscosity (Pa.s), E_a is the activation energy (J.mol^{-1}), R is the universal gas constant (J.K^{-1}.mol^{-1}), T the absolute temperature (K), and C is empirical constant.

2.9.3 Factors influencing yield stress

In the engineering and materials science fields a yield stress is defined as the critical stress that is required to begin plastic deformation and flow of a substance (Chhabra & Richardson, 2008). This means that a material will resist deforming and when sludges are being pumped or mixed this should be taken into consideration. Seyssiecq *et al*. (2003), stated that the existence of yield stress is owing to the solid particles opposing deformation until there is enough applied shear stress that surpasses the yield strength of the solid phase.

Mori and co-workers (2006) and Li and co-workers (2012), found that the yield stress increases exponentially with increasing sludge TSS.

Mori *et al*. (2006) evaluated the TSS (raw activated sludge) effect in the region of 27 g/L to 57 g/L using a rotational and controlled stress rheometer fitted with concentric cylinder geometry. They also established an exponential increase of yield stress with TSS with the relative error of 19%.

Li *et al*. (2012) studied the solid contents effect on the resultant rheological properties for sludge using a controlled shear stress rheometer fitted with plate-plate geometry, they tested three different kinds of sludge with and without polymer conditioning, including anaerobically digested sludge (ADS), activated sludge (AS), and water treatment residuals (WTR). They established an exponential increase of yield stress with TSS for the conditioned AS, ADS, raw ADS and the raw WTR, whereas for raw AS there was no regression equation determined. The yield stress for conditioned WTR displayed a poor exponential relationship with the TSS ($R^2 < 50\%$). The solids concentration ranged from 22.18g/L to 66.53 g/L for AS, from 37.46 g/L to 84.29 g/L for ADS and from 57.49 g/L to 95.82 g/L WTR.

The existence of a three-dimensional network of flocs is commonly associated with the yield stress of suspensions (Seyssieq *et al*., 2003). Markis *et al*. (2014), attributed a stronger network structure to the strengthening of particle interactions that is induced by an increase in solids concentration. Yen *et al*. (2002), affirmed the point that characterisation of the network strength is highly possible with the rheometric tools available at the industry’s disposal. Yuan and Wang (2013) were of the view that by decreasing the network strength of activated sludges, a huge opportunity might be created in the improvement of its dewatering capabilities. The preceding discovery was borne when they explored the properties of activated sludge before and after EPS extraction. They felt that a certain EPS fraction could be a ground-breaker in the dewaterability and drying processes for that particular sludge. Loosely-bound, tightly-bound, pellets and the contribution of slime are understood by Yuan and Wang (2013) to contribute to the network structure of activated sludges.

Sludge network strength is a very important rheological characteristic that can be directly linked to the optimum dewaterability and sludge conditioning if it is well employed. Seyssieq *et al*. (2003) earlier underlined that the three-dimensional network of flocs is related to the yield stress of wastewater sludge suspensions. Yet for optimum dewatering to be effected shearing of the physical and chemical bonds must succeed. In light of literature reviewed by Abu-Orf and Ormeci (2005) with regards the subject matter of network strength, they concluded that practitioners need to design a particular sludge network for a particular dewatering device in mind.

Tixier *et al*. (2003) investigated the sensitivity of rheological characteristics to changes in sludge quality of filamentous suspensions, the sample with low TSS concentration out of four different samples was the one with the highest value for rHA. rHA is a good measure for monitoring the rapid growth or the proliferation of filaments in activated sludge. These filaments get entangled in a network against each other inducing resistance to shear flow. Flow will only show when shear stress surpasses this filamentous network strength (Tixier *et al*., 2003).

2.9.4 Sludge rheological characterisation

The rheological models used for predicting the apparent viscosity and yield stress with different degrees of complexity (i.e. the number of parameters they contain) were discussed in section 2.8.5 This section discusses the practical application of rheological models that have been used at different WWTP processes.

Extensive research has been conducted on wastewater sludge particularly activated sludge, but opinion is divided as to which rheological model works best in predicting the rheological behaviour of this material.

It was mentioned that most researchers have used flow models such as power-law, Bingham, Herschel-Bulkley and Casson. Nonetheless, out of these flow models, the power-law and Bingham models are mostly used in characterising sludge rheology, their particular application depends on whether the sludge has yield stress. A few rheological equations used by the different authors to represent the shear-thinning, viscoplastic or viscoelastic properties of activated sludge were cited from Ratkovich *et al*. (2013) and are is given in Table 2.6.

Table 2.6: Overview of rheological models applied in wastewater sludge (adapted from Ratkovich *et al*. (2013))

Reference	Type of activated sludge	Shear rate range (s^{-1})	Model
Sanin (2002)	WWTP	1.8 to 73.4	Power law
Yen *et al*. (2002)	Dewatering	0 to120	Not mentioned
Tixier *et al*. (2003a); Tixier *et al*. (2003b); Guibaud *et al*. (2005)	WWTP	0 to 800	Power law and Bingham
Guibaud *et al*. (2004)	WWTP	0 to 500	Bingham
Mori *et al*. (2006)	WWTP	0 to 3000	Power law, Bingham and Herschel-Bulkley
Pevere *et al*. (2007)	Anaerobic AS of MBR and CSTR	0 to 800	Power law, Bingham and Casson
Slatter (2001); Slatter (2004)	Thickened AS	5 to 75	Bingham
Akkache *et al*. (2013)	Aerobic AS	0 to 800	Herschel-Bulkley
Baroutian *et al*. (2013)	Mixed sludge (primary & secondary)	10 to 1000	Herschel-Bulkley
Ruiz-Hernando *et al*. (2013)	Secondary sludge	5 to 300	Power law
Markis *et a*l. (2014)	Thickened primary sludge and secondary sludge	0 to 1000	Herschel-Bulkley

2.9.5 Rheometry for wastewater sludge

A number of studies pertaining to municipal wastewater sludge have been done experimentally considering all kinds of rheological measurement parameters in accordance with the rheological behaviour of interest.

Mori and co-workers (2006) pointed out that to be able to rheologically characterise a complex material such as WWTP sludge correctly, it is essential to pay high attention to the choice of relevant measuring geometries and experimental procedures. There is, however, no standardised rheological measurement method available to date. Therefore, researchers fix the measurement parameters that suit best their own experimental tests by minimising or excluding factors that are likely to compromise the results.

For example, Akkache and co-workers (2013); Aranowski and company (2010); Baroutian and co-workers (2013); Djafari and company (2013); Markis and co-workers (2014) and Tixier and co-workers (2003), all used rotational rheometer to characterise wastewater sludge.

The rheometer used by Barountian and co-workers (2013), was fitted with a parallel plate geometry (60 mm diameter, 500 μm gap). A constant shear stress was first imposed in order to pre-shear the sludge prior to measurements. After the pre-shearing step, the tests were carried out by applying different shear rates ranging from 10 s^{-1} to 1000 s^{-1} using a logarithmic ramp, in order to decrease the initial acceleration and the effects due to instrument inertia.

Tixier *et al*. (2003) used a coaxial cylindrical geometry with a double gap measuring system.

Akkache *et al*. (2013) used a Couette geometry with a 1 mm gap in a controlled shear stress mode. A pre-shear at 12 Pa for 1 min followed by a continuous linear ramp imposed from 0.1 Pa to 12 Pa over a period of 8 min were successively applied to the sample.

Markis *et al*. (2014) used a rheometer equipped with a wide gap vane geometry (diameter of the cup, D_c = 39.0 mm; diameter of the vane, D_v = 25.0 mm; height of vane, H = 70.0 mm). The vane geometry was employed to avoid artefacts such as the inertia and end effect. True shear rates can however not be obtain with a vane geometry.

Markis *et al*. (2014) conducted rheological measurements using a controlled stress rheometer equipped with the concentric cylinder geometry (D_c = 32.0 mm; D_b = 29.4 mm; L_b = 44 mm). The tests were as follows:

- Flow curve (decreasing ramp starting at high-stress corresponding to shear rate of 1000 s^{-1}).
- Creep test (below and above yield stress).
- Shear stress sweep test (at various times of rest from 60 to 3600 s).
- Prior to each measurement, the sample is pre-sheared for 600 s at high stress corresponding to a shear rate of 1000 s^{-1} and allowed to rest for 60 s.

Yuan and Wang (2013) performed rheological tests using a rotational rheometer fitted with a PP 50 plate and plate geometry with 49.94 mm diameter and 2.0 mm gap. Their measuring protocol was as follows:

- Increasing shear rate from 0.1 s^{-1} to 1000 s^{-1} in a logarithmic manner;
- Maintaining constant shear rate at 1000 s^{-1} for 30 s;

- Decreasing shear rate in a logarithmically manner from 1000 s^{-1} to 0.1 s^{-1}.

2.9.6 Challenges encountered in rheometry

The following researchers Markis *et al*. (2014); Estiaghi *et al*. (2013) and Seyssieq *et al*. (2003) highlighted that sludge is a complex material but the lack of rheometry uniformity in techniques employed, hinders the effective characterisation of the material as well as the design and optimisation of wastewater treatment plants. Additionally, the nature of complex biological systems is that they are non-Newtonian often with time-dependent behaviour. The way in which a sample is prepared for testing has a great impact on experimental results. The type of viscometer that is used in conducting the experimental works also impacts on the results. Haldenwang and co-workers (2006) rheologically tested two suspensions (3.85%CMC and 10.5%Kaolin) with tube and rotational viscometer. The rheological properties obtained from the rotational rheometer data, were significantly different to that from tube viscometer. Seyssieq *et al*. (2003) noted that if a suspension has not been pre-sheared, then the floc structure is strongly intact and therefore the viscosity is high whereas, if a suspension has undergone pre-shearing, the floc or particles are to an extent disrupted, which tends to decrease the apparent or observed viscosity when sheared. Ratkovich *et al*. (2013) investigated a wide experimental viscosity database; and arrived at the conclusion that as long as experimental protocol differs, so will the persistent lack of correlation in results.

2.10 Overview and conclusion

This chapter provided an introduction to wastewater treatment plant and the various processes of sludge treatment and types of sludge conditioning agents. The principles of sludge dewatering processes were discussed, including belt filter presses, pressure filter presses and centrifuges. The operating parameters such as solids feed, sludge flow rate, polymer dosage, and belt speed and tension were identified as being critical to efficiency and optimisation for BFPs. No correlation has been established between operating parameters and either production or cake solids percentage. Previous researchers indicated that well-described rheological properties of sludge offer a reliable tool for the optimisation of dewatering operations and sludge conditioning at wastewater treatment plants. Krzeminski *et al*. (2012) indicated that sludge characteristics varies from season to season and have influence on the performance of the full-scale membrane bioreactor treating a municipal wastewater.

The basic principles of rheology and the application in wastewater sludge were presented. Flow models used to characterise wastewater sludge and factors affecting the rheology of wastewater sludge characteristics were reviewed.

The rheometry used in wastewater sludge and their experimental challenges were presented. Opinions are divided as to whether wastewater sludge behaves as Bingham or shear thinning fluid. Rotational rheometry seems to be the favourite of researchers to characterise wastewater sludge. However, geometries used and experimental conditions vary widely.

There has been little work done to understand the effect of operating parameters on the yield stress and performance for BFPs and the interactions between the operating parameters have not been reported. With the use of a 3 level Box-Behnken factorial trial, the significance of key parameters will be evaluated and the corresponding parameter interactions will be identified and analysed.

Chapter 3 Research methodology

3.1 Introduction

This chapter presents details of the apparatus, experimental procedures, and materials used to gather data for the evaluation of the rheological properties and moisture content of the sludge. Included also are descriptions of the operating procedures for the instruments and equipment used and the rheological characterisation procedure applied to the measured experimental data.

3.2 Research design

The research design technique used in this study was a quantitative experimental research. This study consisted of two parts, the first part was to understand the variability of rheological properties of the secondary sludge that feeds the belt filter press before polymer addition and also after it has been added. The second part was the factorial trial for optimising the BFP at Plant K WWTP.

3.3 Experimental details

Four WWTPs (Plant J, K, L and M) were chosen for this research work and these WWTP are owned and some are partly managed by the City of Cape Town. The WWTP names and their areas of locations are not disclosed for confidentiality purposes. The process flow diagrams of WWTPs used in the work can be found in the Appendix C Wastewater treatment plants process flow charts. These plants were selected on the basis that they were operating dependably without any major breakdowns and therefore could provide sludge samples consistently. Due to limited resources, a wider area could not be covered. Rheological tests were conducted at the Cape Peninsula University of Technology, Flow Process and Rheology Centre for the first part. Sludge samples from these WWTPs were collected and experimentally tested over a period of twelve weeks. Each WWTP was sampled once a week and two plants were sampled on the same sampling day. The samples were collected weekly from 7 July 2015 to 24 September 2015 as shown in Table 3.1. For the second part, the rheological tests were conducted on site at Plant K WWTP.

Table 3.1: Sampling dates at each WWTP

WWTP	***Sample Dates: 2015***																							
	July								August								Sept							
	7	9	14	16	21	23	28	30	4	6	11	13	18	20	25	27	1	3	8	10	15	17	22	24
Plant J	✓		✓		✓		✓		✓		✓		✓		✓			✓	✓			✓		✓
Plant K	✓		✓			✓		✓		✓		✓		✓		✓	✓		-	-	✓		-	-
Plant L		✓		-	✓		✓		✓		✓		✓		-	-		✓	✓			✓		✓
Plant M		✓		✓		✓		✓		✓		✓		✓		-	✓			✓	✓		✓	

Amongst these plants, Plant K was the only plant that was thickening the sludge prior to dewatering. All the plants at the time of sampling were using the same flocculant (Flopam FO 4800).

3.3.1 Sampling method

In order to evaluate the rheological properties for unconditioned and conditioned sludges, samples were collected from the feed stream to the belt filter press before the dosing of the flocculant and after dosing the flocculant on the linear screen (gravity drainage zone) at three different points (100 cm, 200 cm, and 300 cm). These samples were tested within 4 hours after sampling. During transportation, the samples were kept at 15 ºC below ambient temperature to minimise sludge bacterial activity. The sampling points on the gravity drainage zone are shown in Figure 3.1.

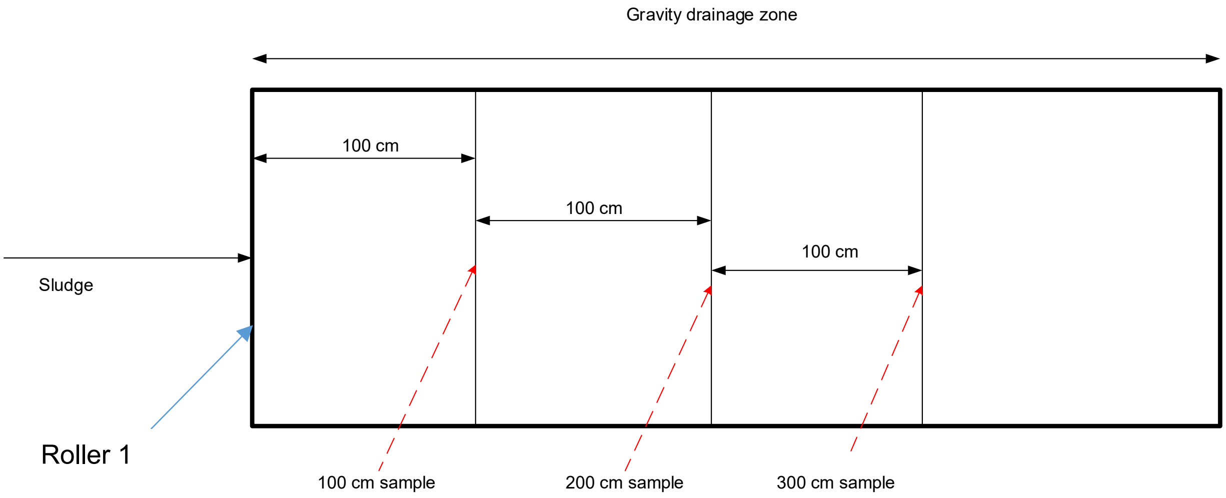


Figure 3.1: Gravity drainage zone of a belt filter press

3.3.2 Factorial trial

Response surface methodology based Box-Behnken Design (BBD) statistical method is favoured to compute the relationship between input variables and output variables. One of the advantages of BBD is that it is a spherical, rotating design. The central point and the middle points of the edges of the cube confined on the sphere (Kumar *et al*., 2008). Montgomery (2012) pointed out that BBDs generally permits each factor on three levels and fitting the second-order polynomial model effectively.

In the current study, a four factor three level Box-Behnken experimental design was used to statistically analyse the effect of operating parameters and their interactions on the BFP performance using Stat-Ease Design Expert V 10.0.0 version. The selected parameters were polymer concentration (%wt), polymer dosing rate (m^3/hr), sludge feed rate (m^3/hr) and belt filter press speed (%) and their ranges are shown in Table 3.2. These parameters were evaluated by studying their effect on final sludge cake solids concentration (%wt), yield stress and a viscosity at 100 cm from the start of the BFP, filtrate suspended solids and lastly on the solids capture. The factors require being run at only three levels that are represented by codes −1 (low), 0 (central or middle point) and 1 (high) (Mahdavi & Monajemi, 2014).

Table 3.2: Factors in Box-Behnken experimental design

Factors	Variable	Levels used		
		Low	Medium	high
Polymer concentration (%)	A	0.2 (-1)	0.25 (0)	0.30 (+1)
Polymer dosing (m^3/hr)	B	0.7 (-1)	0.8 (0)	0.9 (+1)
Sludge feed (m^3/hr)	C	10 (-1)	15 (0)	20 (+1)
Belt speed (%)	D	90 (-1)	105 (0)	120 (+1)

After selection of process operating variables and their ranges, experiments were established based on a BBD which consisted of twenty-nine experiments with five centre points. Design expert software designed the experiment in a random pattern. Randomisation of experimental runs warrants that the conditions in one experimental run neither be influenced by the conditions of the preceding runs nor predict the conditions in the succeeding runs. Randomisation of experiments is important for the interpretation of results and drawing conclusions from the experiment in an accurate, unambiguous and defendable manner. The twenty-nine tests were conducted at Plant K within over a period of four days. The plant was allowed to run for 30 minutes per test and samples were collected in this time. The belt speed 100% corresponds to 0.062 m/s. A full experimental matrix is shown in Table 3.3.

Table 3.3: Box-Behnken experimental matrix

Run order	A: Polymer concentration	B: Polymer dosing	C: Sludge feed	D:Belt speed
	%	m^3/hr	m^3/hr	%
1	0.3	0.8	15	120
2	0.25	0.7	20	105
3	0.2	0.8	15	120
4	0.25	0.8	15	105
5	0.25	0.9	20	105
6	0.25	0.7	15	120
7	0.25	0.9	15	90
8	0.25	0.8	10	120
9	0.25	0.8	20	120
10	0.25	0.8	15	105
11	0.25	0.8	15	105
12	0.3	0.7	15	105
13	0.25	0.8	20	90
14	0.25	0.7	15	90
15	0.25	0.9	15	120
16	0.2	0.7	15	105
17	0.3	0.8	10	105
18	0.2	0.9	15	105
19	0.25	0.9	10	105
20	0.3	0.8	15	90
21	0.25	0.8	15	105
22	0.2	0.8	15	90
23	0.25	0.7	10	105
24	0.2	0.8	10	105
25	0.3	0.8	20	105
26	0.25	0.8	15	105
27	0.25	0.8	10	90
28	0.3	0.9	15	105
29	0.2	0.8	20	105

3.4 Research apparatus

The following apparatuses were used to collect data and to measure rheological properties:

3.4.1 Honey jars

A water-tight 200 ml honey jars as shown in Figure 3.2 were utilised for the collection of the sludge samples.

Figure 3.2: Water-tight 200 ml honey jar for sampling

3.4.2 Thermo-electrical cooling box

A wheeled 40-liter thermoelectric cooler supplied with a 12 and 220V cords was used for sample carriage. The cooling box has a temperature rating performance of 15ºC below ambient temperature. It helps to arrest changes in biological microscopic structure as the temperature is one of the factors that give rise to rheological characteristics. The main purpose of the cooling box was to maintain the sampled material in good biological state until the time of rheological experimental testing. The 40-liter wheeled-cooling box photo is herein shown Figure 3.3:

Figure 3.3: Thermo electrical cooling box

3.4.3 Rheometer

A Paar-Physica MCR-51 rotary rheometer was used for determining rheological characteristics of different materials including sewage suspensions and sludges. The rotational type rheometer is the most favoured by wastewater sludge rheologists across the world due to its ease operation and small sample required. The rheometer applies a torque on the material at a measured shear rate to determine the corresponding shear stress. For this research, it was fitted with a parallel-plate geometry with a measuring cell CP50 of 50 mm diameter and a gap of 1 mm. The parallel plate geometry was chosen over the cone and cup geometry due to its ability to shear suspension/sludge material from fluid feed pre-poly addition to more viscous sludges. The MCR-51 rheometer is operated on a limiting minimum torque of 250 μNm. It also has a maximum particle size of 5 μm for the chosen plate-plate geometry. The rheological tests were conducted in the controlled shear rate mode with the shear rate being the control parameter. Rheological measurements were performed by decreasing linearly shear rate from 800 s^{-1} to 0 s^{-1} in 3 minutes. Thirty data points were collected and each point was measured for 5 s. The volume of the sample was 2 ml, this sample volume has been used by other researchers such as Baroutian *et al*. (2013); Mori *et al*. (2006); Lotito and Lotito (2014). This protocol was repeated three times for each sludge sample in the honey jar to ensure reproducibility of the measurements. The Paar-Physica MCR-51 rheometer is shown in Figure 3.4:

Figure 3.4: Rotational-type rheometer (Paar-Physica MCR-51)

3.4.4 Water bath

The unit incorporates a temperature controller with a LED display, heater, and circulation pump. The temperature was set at 23°C (±1°C) for this particular rheological experimental research. The temperature was controlled by a water bath supplied by Kimix (Pty) Ltd shown in Figure 3.5. It is always paramount to link rheology testing with a particular temperature for proper material characterisation.

Figure 3.5: Water bath

3.4.5 Moisture analyser

The moisture analysis of the wastewater suspensions and sludge under rheological experimentation were conducted with the moisture analyser AND ML-50 illustrated in Figure 3.6. This device can be considered to be fairly fast and accurate when compared to the oven where samples have to be left overnight. A sample of 2 g size was placed on the foil plates with a spatula for the burning of the moisture content. Results of solids concentration from the moisture analyser experimentation are measured in mass percentage (%TS). Before the experiments were conducted the 200 ml honey jars were hand shaken to ensure the sample is well mixed and homogenous. The sample were selected at the centre of the belt. The measurements were repeated three times and the average solids mass percentage was taken.

Figure 3.6: AND ML-50 moisture analyser

3.4.6 Belt filter press

The belt filter presses used at the four plants are shown in Figure 3.7. Plant J and Plant L WWTPs were using similar dewatering systems supplied by Siemens as shown in Figure 3.7a. The Plant M dewatering system is shown in Figure 3.7b. Plant K was using a dewatering system supplied by Solids Technology as shown in Figure 3.7c.

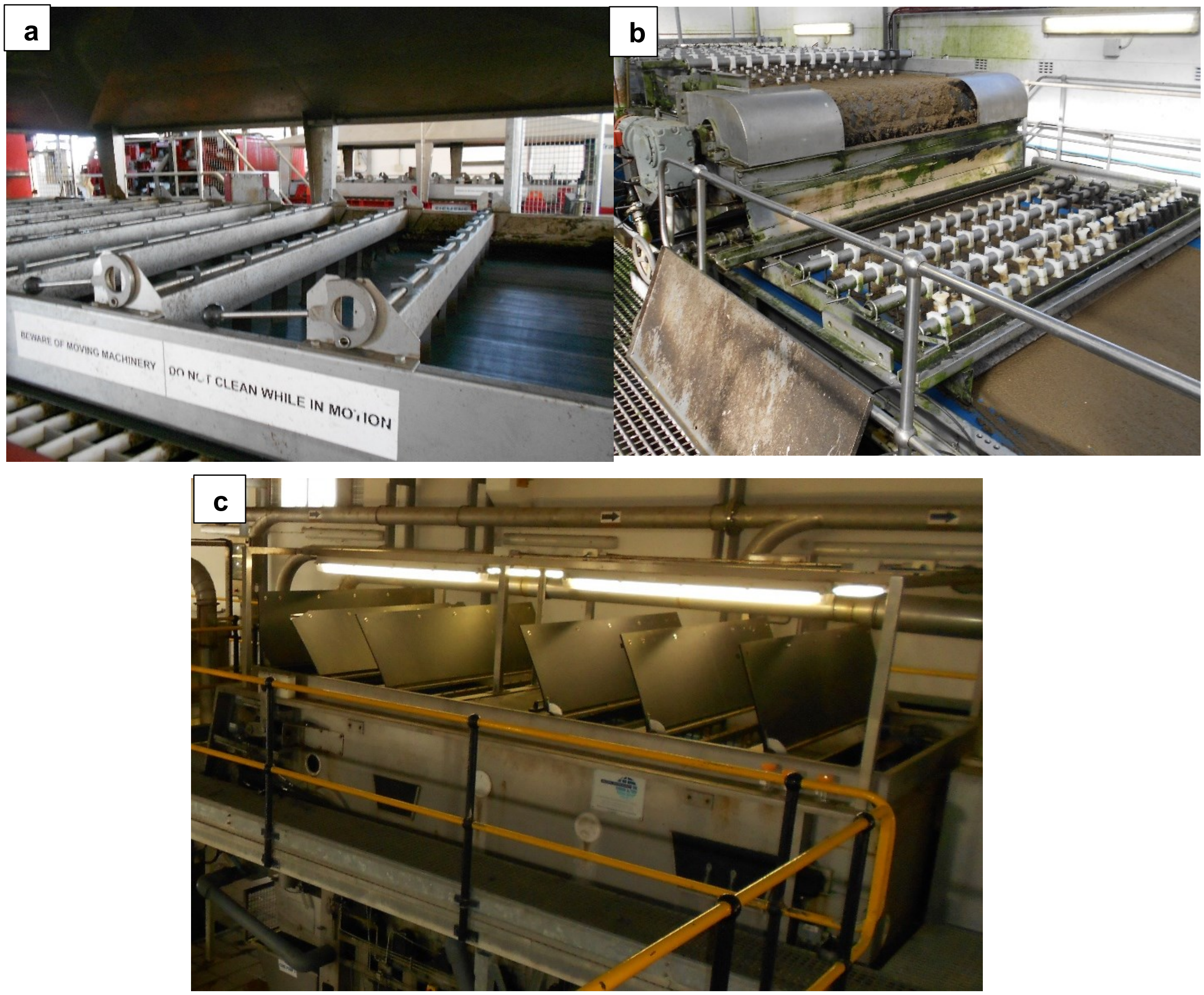


Figure 3.7: Dewatering systems at different wastewater treatment plants (a) Plant L and Plant J WWTPs (b) Plant M WWTP (c) Plant K WWTP

3.5 Analysis and presentation of results

3.5.1 Rheological characterisation

Data was imported from the rheometer software called Rheoplus via the utilisation of universal memorial bus stick for transferring data to a laptop. Flow curves of shear stress and the shear rate were done in order to attain a graphical representation of the material rheological behaviour. For analysis, only the shear rate range of 600 s^{-1} to 200 s^{-1} was considered, because at a shear rate below than 200 s^{-1} the critical torque range of the rheometer was reached, and the accuracy of the equipment was compromised. A Bingham model was used to determine the viscosities and the yield stresses of both conditioned and unconditioned sludges by means of linear regression. Each rheological test was carried out three times per sample and the average value was taken.

3.5.2 Analysis of factorial trial data

A suitable approximation for the accurate functional link between the independent variables and the response surface was identified to fully optimise the responses assessed, using the following second order quadratic polynomial model for the RSM Box-Behnken design:

$$Y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} b_{ij} x_i x_j + \varepsilon$$

Analysis of variance (ANOVA) was performed in order to determine significant differences between factors. The evaluation of significance for the controlling factors was done by calculating the F-ratio, sum of squares (SS), degree of freedom (DF), mean of square (MS), and F-test of significance (5% or 0.005) (F-values) were calculated.

The least square method was used to fit a model equation by minimising the residual error measured by the sum of square deviations between the measured and the predicted responses. This involved the calculation of estimates for the model coefficients (b_0, b_i, b_{ij}, $b_{ii,}$). The model equation or the calculated coefficients are estimated firstly and then verified for statistical significance (Noordin, et al., 2004). The significance of the model and all the model terms were evaluated statistically using the F-ratio at probability (p) of 0.05. The p-value tests the statistical significance of the estimated correlations. A p-value less than 0.05 indicate the model and model terms are statistically significant at the 95% confidence level (Mahmoud *et al*., 2011; Noordin *et al*., 2004 & Amenaghawon *et al*., 2013). The fitness of the model was checked in order to determine whether the model actually describes the experimental data and it was evaluated by the correlation coefficients R^2, the fraction of the variation explained by the model (Noordin *et al*., 2004). These R^2 coefficients have values between 0 and 1. All the statistical analysis were performed with Design-expert V10. After the model fitted for each response, three-dimensional (3D) surface graphs and contour plots were generated using the same software to study the interactive effect of independent variables on the responses.

3.6 Conclusion

The apparatus, experimental procedures, and materials used to gather data for the evaluation of the rheological properties and moisture content of the sludge have been described. Four WWTP were selected based on operational dependability for assessment of sludge rheological properties over twelve weeks. This was followed by a 3-level, 4-factor Box-Behnken factorial trial at Plant K WWTP to evaluate the effect of polymer concentration, polymer dosing rate, sludge flow rate and belt speed on the resulting sludge rheological properties, sludge cake solids and filtrate suspended solids. The results of the variability assessment of sludge rheological properties are discussed in Chapter 4 and the results from the factorial trial are discussed in Chapter 5.

Chapter 4 Variability of sludge rheology in various WWTPs

4.1 Introduction

The aim of this research was to characterise the rheological behaviour of the secondary sludge from various WWTPs in the city of Cape Town. During the course of this work, only four plants were considered due to their operational dependability. In this chapter the results and the discussions pertaining to the determination of different rheological properties used to characterise the secondary sludge under investigation are presented. They include:

- WWTP process conditions
- Flow curves and Bingham parameters.
- Variation of feed sludge and dry cake solids concentration
- Bingham parameters versus concentration

The samples were collected at the last step of the WWT process, the belt filter presses over a twelve weeks period.

4.2 WWTP process parameters

The rheological properties of the secondary sludge can be affected by the plant process parameters such as the polymer dosage rate, the sludge feed rate, and the belt speed. The belt filter press performance of all the plants tested was determined by measuring feed sludge solids concentration and comparing it to the final filter cake solids concentration. During the duration of the experimental work, plant process parameters were also assessed. Table 4.1 to Table 4.4 illustrate the calculated and measured plant process parameters. All the plants used a constant polymer concentration of 0.25% except for Plant M which used 0.3%. The polymer concentration was therefore not measured and accepted to be constant. The variability of process parameters was determined by calculating the average and the standard deviation (SD). For comparing the variability of the process parameters for each plant, a coefficient of variation (CV) was calculated for each plant. CV measures the variability of a data independently of the unit of measurement used. It therefore, eliminates the unit of measurement of the SD of a data by dividing it by the mean of the data point. The CV indicates how large the SD is in relation to the mean. It was noted that polymer dosing rate, sludge feed flow rate, linear screen and belt press speed were all varying from week to week for the plants. However, the overall process parameter variability as indicated by the CV was lower for Plant K followed by Plant L and Plant J. Though Plant M had high process parameter variability, its linear screen speed had the lowest variability with only ±3% CV. It can be noted that Plant K plant has lower sludge feed flow rate and higher polymer dosing compared to other plants. This was the consequence of using the sludge thickening process prior to the dewatering process which increased the sludge solids load and considerably reduced the sludge volume load on the belt filter press.

Table 4.1: Plant J operating conditions

	Poly rate (m^3/h)	**Sludge feed rate (m^3/h)**	**Press speed (m/s)**	**Linear Screen (m/s)**
Week 1	0.66	63.44	0.04	0.26
Week 2	0.44	54.00	0.04	0.26
Week 3	0.48	48.25	0.04	0.31
Week 4	0.64	59.65	0.03	0.20
Week 5	0.63	64.14	0.03	0.21
Week 6	0.40	43.35	0.03	0.20
Week 7	0.50	61.44	0.04	0.25
Week 8	0.68	60.10	0.04	0.20
Week 9	0.61	62.00	0.05	0.31
Week 10	0.50	60.00	0.04	0.20
Week 11	0.54	60.15	0.03	0.26
Week 12	0.65	60.20	0.04	0.20
Average	0.56	58.06	0.04	0.24
SD	±0.10	±6.33	±0.01	±0.04
CV	±17%	±11%	±16%	±18%

Table 4.2: Plant K operating conditions

	Poly rate (m^3/h)	Sludge feed rate (m^3/h)	Press speed (m/s)	Linear Screen (m/s)
Week 1	0.975	15.74	0.058	0.058
Week 2	0.999	15.10	0.058	0.058
Week 3	0.998	14.02	0.058	0.058
Week 4	0.995	13.94	0.058	0.058
Week 5	0.998	13.92	0.058	0.058
Week 6	1.003	14.02	0.058	0.058
Week 7	1.01	16.00	0.058	0.058
Week 8	0.99	14.02	0.051	0.051
Week 9	1.00	14.00	0.051	0.051
Week 11	0.798	12.06	0.058	0.058
Average	0.977	14.28	0.057	0.057
SD	±0.063	±1.12	±0.003	±0.003
CV	±6%	±8%	±5%	±5%

Table 4.3. Plant L operating conditions

	Poly rate (m^3/h)	Sludge feed rate (m^3/h)	Press speed (m/s)	Linear Screen (m/s)
Week 1	0.65	59.30	0.064	0.310
Week 3	0.61	55.70	0.064	0.310
Week 4	0.62	53.85	0.077	0.310
Week 5	0.61	51.35	0.077	0.310
Week 6	0.61	49.61	0.077	0.356
Week 7	0.70	41.96	0.049	0.226
Week 9	0.72	48.52	0.071	0.226
Week 10	0.78	51.00	0.085	0.268
Week 11	0.60	49.02	0.080	0.268
Week 12	0.80	49.02	0.071	0.310
Average	0.67	50.93	0.072	0.289
SD	±0.08	±4.68	±0.011	±0.042
CV	±11%	±9%	±14%	±14%

Table 4.4. Plant M operating conditions

	Poly rate (m³/h)	Sludge feed rate (m³/h)	Press speed (m/s)	Linear Screen (m/s)
Week 1	0.55	14.40	0.056	0.087
Week 2	0.95	22.30	0.056	0.087
Week 3	1.1	40.30	0.056	0.087
Week 4	0.95	42.50	0.056	0.087
Week 5	0.95	42.00	0.056	0.087
Week 6	1.0	42.80	0.056	0.087
Week 7	0.95	42.55	0.084	0.087
Week 9	1.0	42.21	0.108	0.082
Week 10	0.9	34.49	0.108	0.082
Week 11	0.9	35.00	0.108	0.082
Week 12	1.0	32.3	0.108	0.082
Average	0.93	35.53	0.077	0.085
SD	±0.14	±9.45	±0.026	±0.003
CV	±15%	±27%	±33%	±3%

4.3 Variability of sludge solids concentration

Samples for the determination of solids concentration were collected at different points in the dewatering process. These samples included:

- the sample representative of the feed
- The sample representative of sludge on the linear screen: three samples were considered at a specific distance from the start of the screen; 100 cm, 200 cm, and 300 cm. Before 100 cm the sludge proved to be difficult to measure rheologically and therefore this was the first point where the sludge could be measured. It was because before 100 cm the sludge flocs and water separates as shear force is applied.
- The sample representative of the final filter cake.

4.3.1 Comparison of solids concentration by plant per week

A comparison of the weekly averages for solids concentration values for sludge feed, linear screen sludge at (100 cm, 200 cm and 300 cm) and sludge cake samples are shown in Figure

4.1 to Figure 4.5. For the 12 weeks results obtained, the feed solids concentration for Plant J varied from 0.03% to 1%, Plant K from 2.23% to 2.73%, Plant L from 0.27% to 0.8% and Plant M from 0.53% to 1%. Table 4.5 to Table 4.9 give the solids concentration for sludge feed, linear screen sludge at (100 cm, 200 cm and 300 cm) and sludge cake. Detailed solids concentration results for these plants can be found in Appendix B Sludge solids concentration. The variability of these samples was determined by calculating the average and the SD. For comparing the variability of the solids concentration for each plant, a CV was calculated for each plant as in section 4.2 . It can be noted that Plant K's feed solids concentration were high and had low CV value of ±6% compared to other plants. The CV values for feed solids concentration at Plant J, L and M range was 21% to 103%. Plant M performed the best, delivering cakes with the highest solids content varying from 12.4% to 17.3% with average and SD of 14.23 ±1.63%, while Plant J (12.33% to 14.73%) and Plant K (12.03% to 14.37%) were quite close to each other with an average and SD of 13.58 ±0.93% and 13.55 ±0.87% respectively, whereas Plant L was the lowest with 10.2% to 14.43% having an average and SD of 11.92 ±1.39% cake solids concentration.

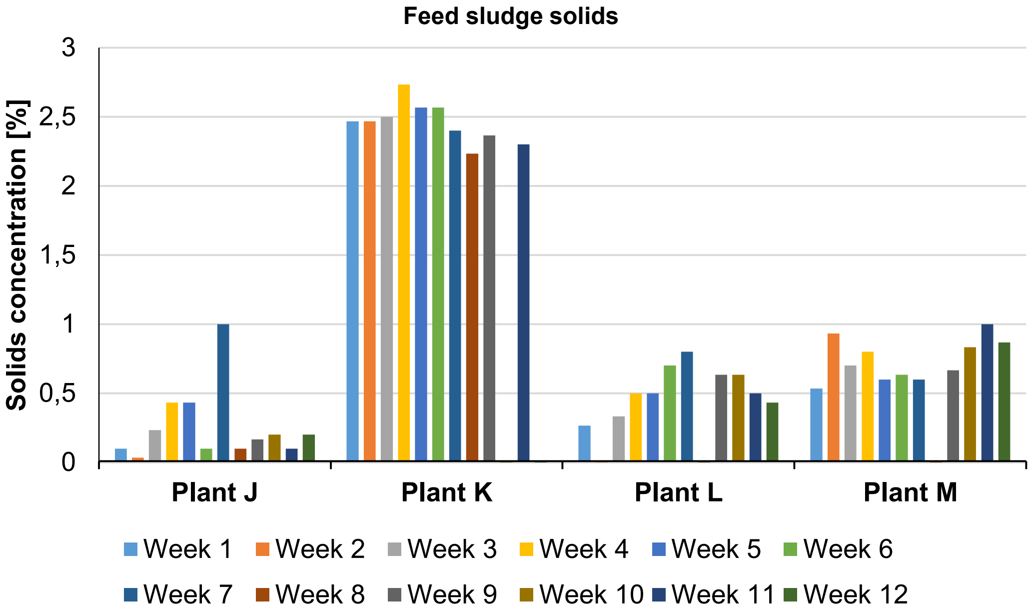


Figure 4.1: Sludge feed solids concentration comparison by plant per week

Table 4.5: Comparison of feed solids concentration average, standard deviation and coefficient of variance for sludge feed samples at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.26	2.46	0.53	0.74
SD	±0.27	±0.14	±0.16	±0.15
CV	±103%	±6%	±31%	±21%

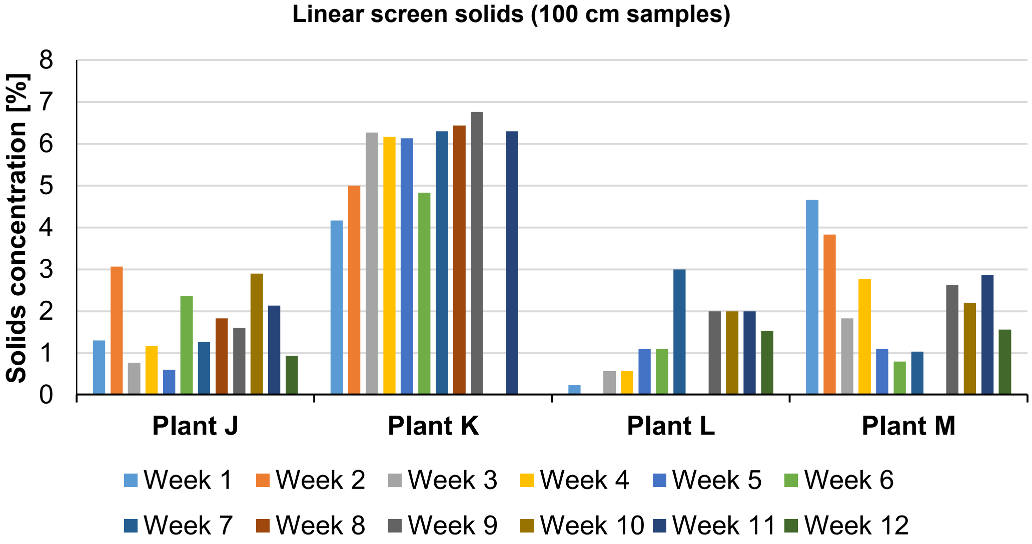


Figure 4.2: Linear screen sludge solids concentration at 100 cm comparison by plant per week

Table 4.6: Comparison of solids concentration average, standard deviation and coefficient of variance for samples at 100 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	1.66	5.84	1.41	2.30
SD	±0.81	±0.85	±0.86	±1.21
CV	±49%	±15%	±61%	±53%

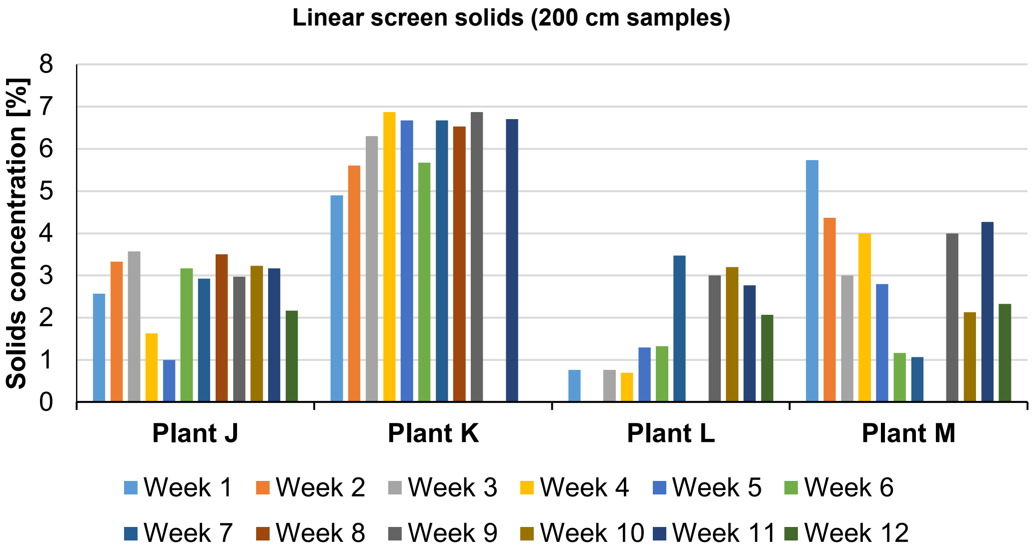


Figure 4.3: Linear screen sludge solids concentration at 200 cm comparison by plant per week

Table 4.7: Comparison of solids concentration average, standard deviation and coefficient of variance for samples at 200 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	2.77	6.28	1.94	3.17
SD	±0.79	±0.66	±1.10	±1.45
CV	±29%	±11%	±57%	±46%

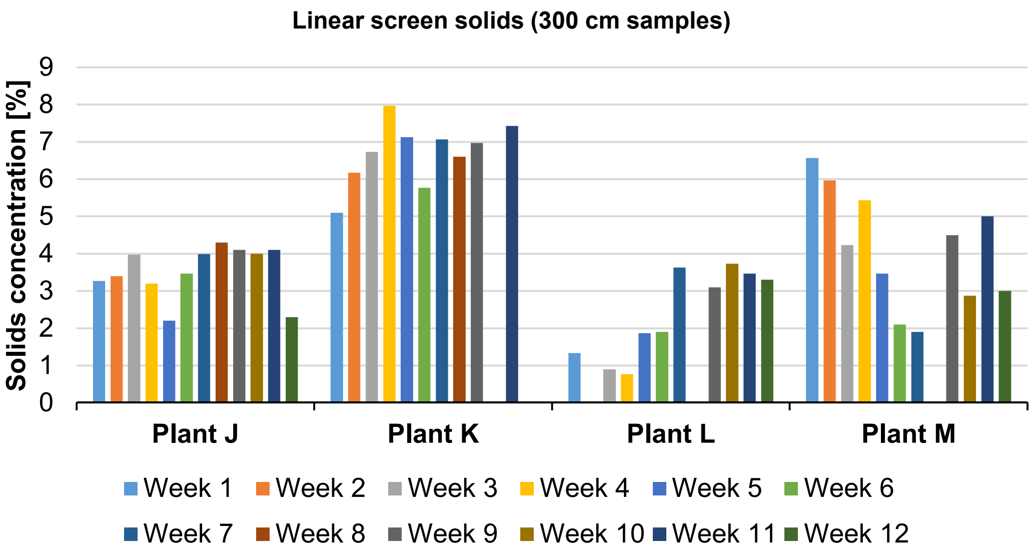


Figure 4.4: Linear screen sludge solids concentration at 300 cm comparison by plant per week

Table 4.8: Comparison of solids concentration average, standard deviation and coefficient of variance for samples at 300 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	3.53	6.69	2.40	4.09
SD	±0.70	±0.83	±1.17	±1.56
CV	±20%	±12%	±49%	±38%

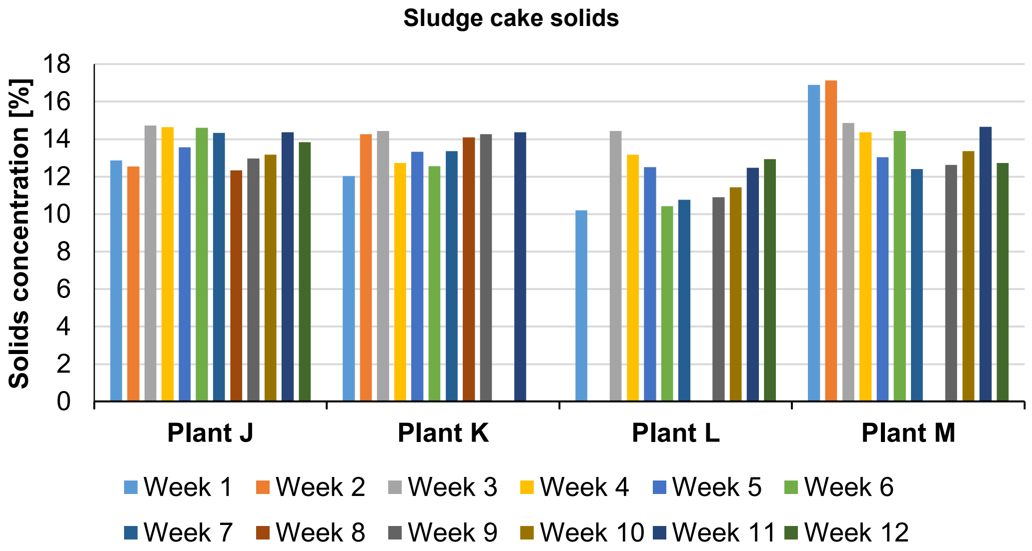


Figure 4.5: Sludge cake solids concentration comparison by plant per week

Table 4.9: Comparison of sludge cake solids concentration average, standard deviation and coefficient of variance at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	13.58	13.55	11.92	14.23
SD	±0.93	±0.87	±1.39	±1.63
CV	±7%	±6%	±12%	±11%

4.3.2 Comparison of solids concentration over time per sample point for each plant

The solids concentration for weekly samples for all plants and a comparison of plant results are given in Figure 4.6. When considering the solids concentration of each plant over the experimental duration, it was observed that there was an increase in solids concentration for the first 100 cm on the linear screen. However, for Plant K and Plant L between 100 cm and 300 cm, there was not much difference in the solids concentration for each plant. It indicates that there is not much free water in the sludge as it is removed in the thickening process. For Plant L, based on observations during the sampling period, the belt filter press seemed to be overloaded with the sludge considering the low solids concentration on the linear screen, hence, the plant produced sludge cake with lower solids concentration compared to other plants as seen in Figure 4.5. It could also be due to inadequate cleaning of the linear screen belt and therefore, the belt gets clogged. For Plant J and Plant L, there is also not much variation for the between 100 cm and 300 cm on the linear screen, but it was observed that the solids concentration were less than 5%. For Plant M, the variability of solids concentration is evident on the linear screen. This is an indication of process parameters that were constantly changing at Plant M on a weekly basis as the CV indicates in Table 4.5 to Table 4.8.

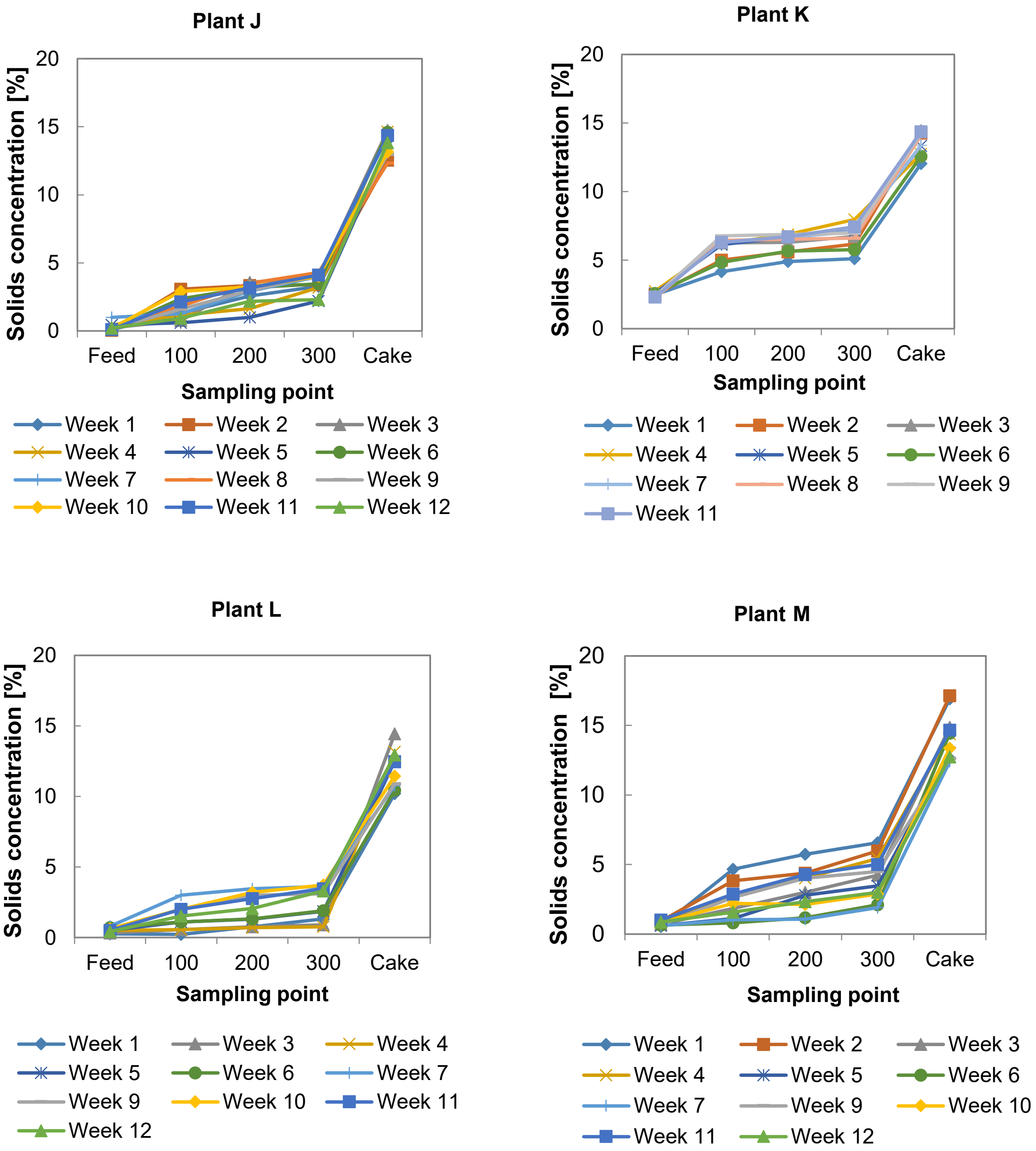


Figure 4.6: Solids concentration over time per sample point for each plant

4.4 Flow curves

To obtain the numerical values of rheological properties of secondary sludge from different WWTPs, the shear stress against shear rate flow curves of the sludge from the four WWTPs was plotted. Graphical representation of the flow curves is for the whole twelve week duration of the experimental period. For analysis, only the shear rate range of 600 s^{-1} to 200 s^{-1} was considered as explained in section 3.5.1 .

4.4.1 Plant J flow curves

Plant J sludge samples flow curves are presented in Figure 4.7, for the feed sludge before polymer conditioning and the samples on the linear screen at different distances at 100 cm, 200 cm, and 300 cm after the sludge conditioning. The feed flow rheograms were quite irregular rheograms. Whereas those from the linear screen samples were smooth.

For dilute feed sludges, at 600 s^{-1} shear rate, the shear stresses were less than 2 Pa. This is the indication of how dilute Plant J's feed sludge samples were. These sludges were characterised with the Bingham plastic model. The coefficient of determination (R^2) for all the samples was above 0.90, except week 1 dilute feed sludge which was 0.52. The high coefficient of determination indicates a high percentage of data points fitting the Bingham model. The low coefficient of determination in week 1 may have been caused by the irregular distribution of the solids particles in the sample during testing. At low solids concentration the sludge behaves as Newtonian fluid (Baroutian *et al*., 2013), thus explaining the low feed yield stress values obtained. The Bingham yield stress and Bingham viscosity model parameters for all the tested samples at Plant J are summarised in Table 4.10. An order of magnitude variance was observed on the Bingham parameters obtained. Al-Dawery (2014) and Travnicek *et al*. (2013), state that due to the non-uniformity of operating conditions, wastewater sludges exhibit different rheological parameters, especially when determined using an empirical correlation.

Table 4.10: Summary of Bingham parameters range from Plant J over 12-week

Sample	Bingham yield stress [Pa]	Bingham viscosity [Pa.s]
Feed	0.011 - 1.17	0.0006 - 0.0032
100 cm	1.23 - 40.74	0.0046 - 0.0542
200 cm	2.64 - 53.79	0.0062 - 0.0678
300 cm	7.33 - 77.21	0.0129 - 0.0969

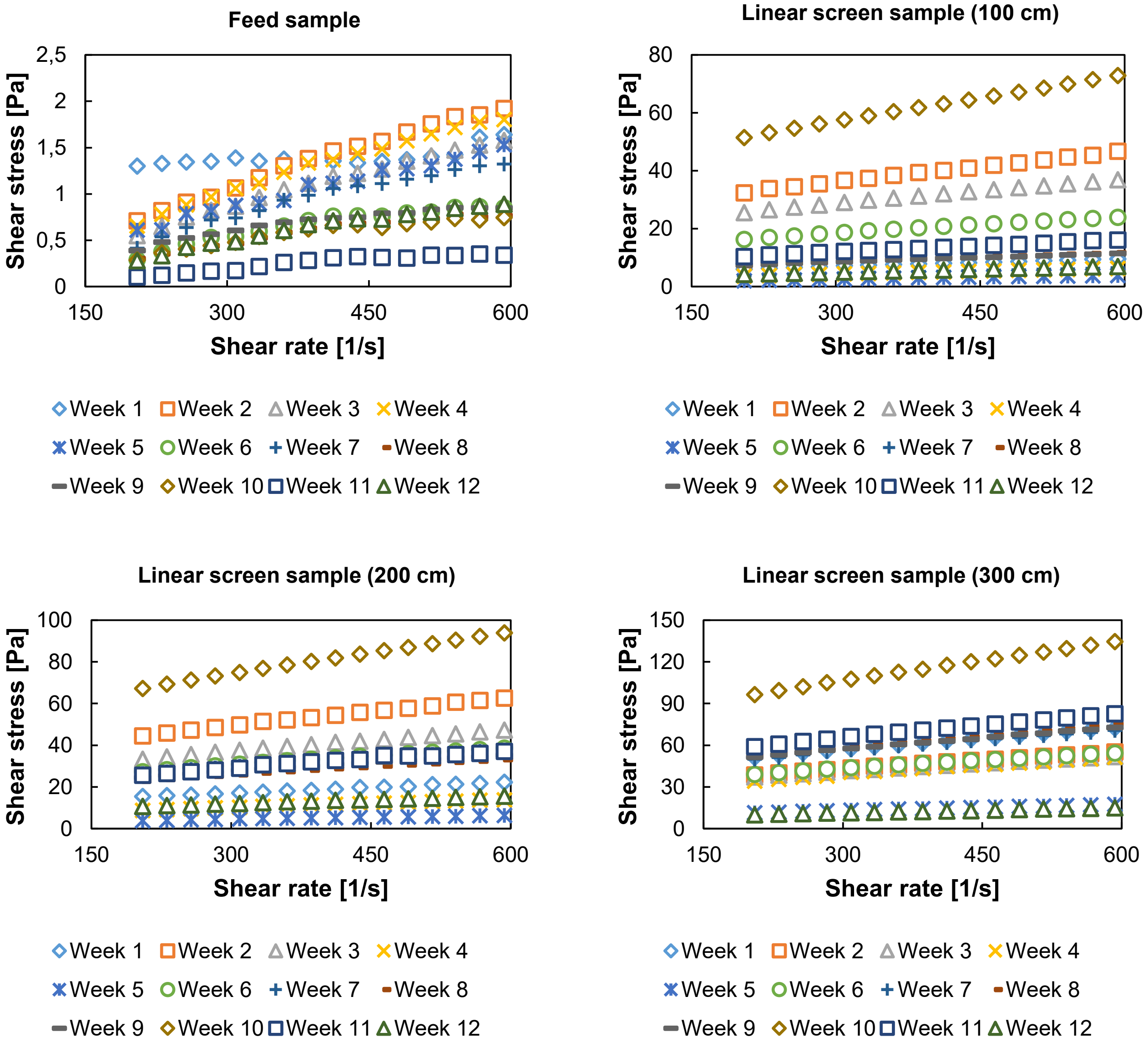


Figure 4.7: Plant J flow curves over the 12-week experimental duration

4.4.2 Plant K flow curves

Plant K sludge samples flow curves are presented in Figure 4.8, for the feed sludge before polymer conditioning and the samples on the linear screen at 100 cm, 200 cm, and 300 cm after the sludge conditioning. The results presented were measured over the twelve (12) weeks experimental duration. However, for Week 10 and Week 12 data is not available due to operational breakdown which occurred at the plant.

The rheograms for all the samples were smooth which are characteristic of a fairly homogenous material. The very smooth appearance of these rheograms were thought to be induced by the dissolved air flotation (DAF) process undergone by the feed at the treatment plant. The Plant K plant sludge was characterised as a Bingham plastic material. The coefficient of determination (R^2) for all the samples was above 0.996. The high coefficient of determination indicates that the Bingham model describes adequately the rheological behaviour of Plant K plant sludge. The Bingham yield stress and Bingham viscosity model parameters for all the tested samples at Plant K are summarised in Table 4.11.

Table 4.11: Summary of Bingham parameters range at Plant K over 12-week

Sample	Bingham yield stress [Pa]	Bingham viscosity [Pa.s]
Feed	11.58 - 16.57	0.0211 - 0.0259
100 cm	61.86 - 168.78	0.07 - 0.3409
200 cm	68.17 - 197.29	0.0804 - 0.2884
300 cm	103.16 - 218.89	0.1337 - 0.3404

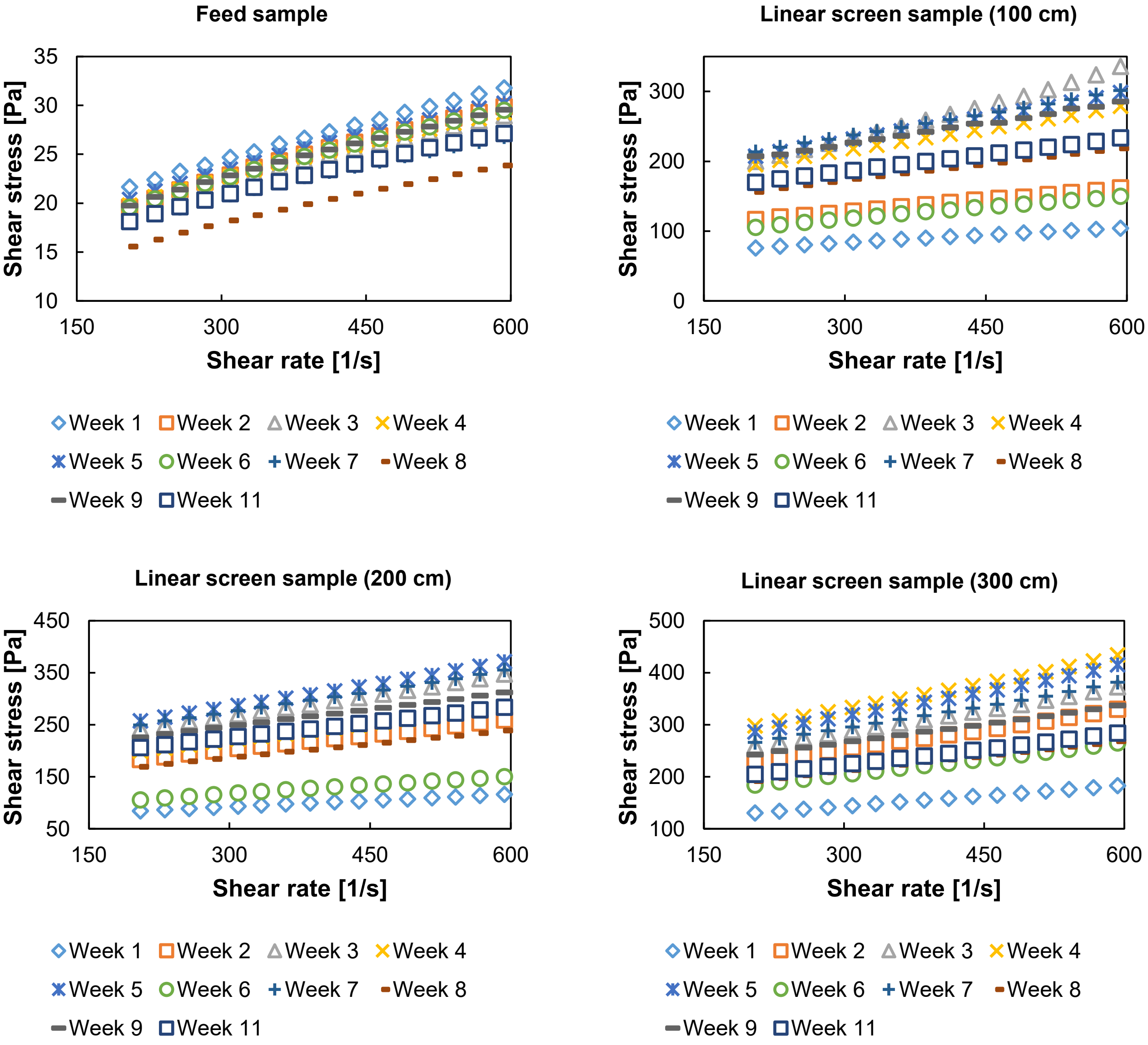


Figure 4.8: Plant K flow curves at various sampling points over the 12-week experimental duration

4.4.3 Plant L flow curves

The flows curves of Plant L are presented in Figure 4.9 for the feed sludge before polymer conditioning and on the linear screen at 100 cm, 200 cm, and 300 cm after the sludge conditioning. Week 2 and 8 data is not available due to operational downtime at the plant.

The feed flow curves are smooth and closely grouped indicating a reasonably homogenous material. For the samples on the linear screen, the results vary considerably. The Plant L plant sludge was characterised as a Bingham plastic material. The coefficient of determination (R^2) for all the samples was above 0.996. The Bingham yield stress and Bingham viscosity model parameters for all the tested samples at Plant L are summarised in Table 4.12.

Table 4.12: Summary of Bingham parameters range at Plant L over 12-week

Sample	Bingham yield stress [Pa]	Bingham viscosity [Pa.s]
Feed	0.13 - 1.50	0.0022 - 0.0045
100 cm	0.71 - 21.51	0.0031 - 0.032
200 cm	0.85 - 43.95	0.0041 - 0.0571
300 cm	2.15 - 67.92	0.0063 - 0.0878

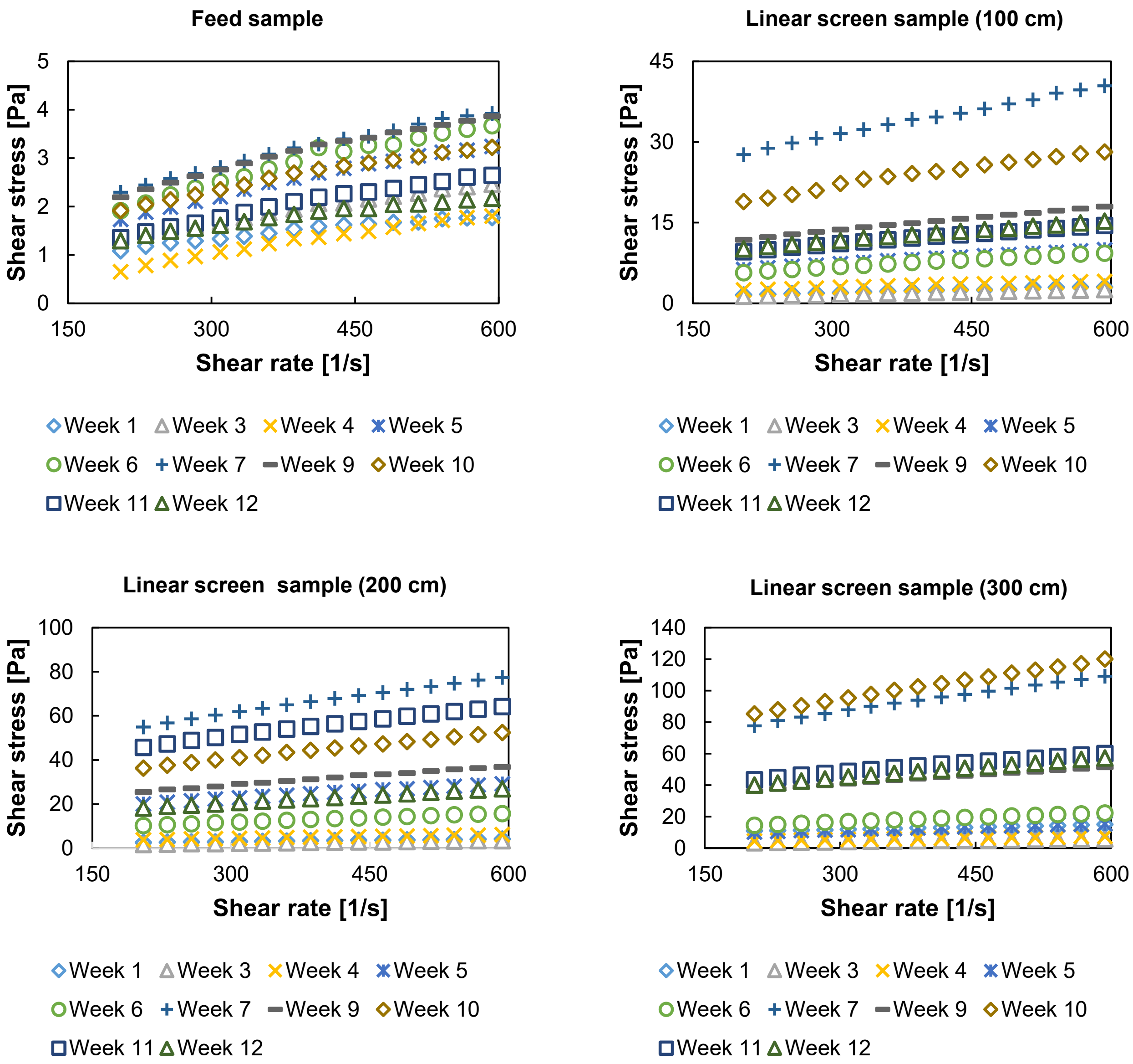


Figure 4.9: Plant L flow curves over the twelve-week experimental duration

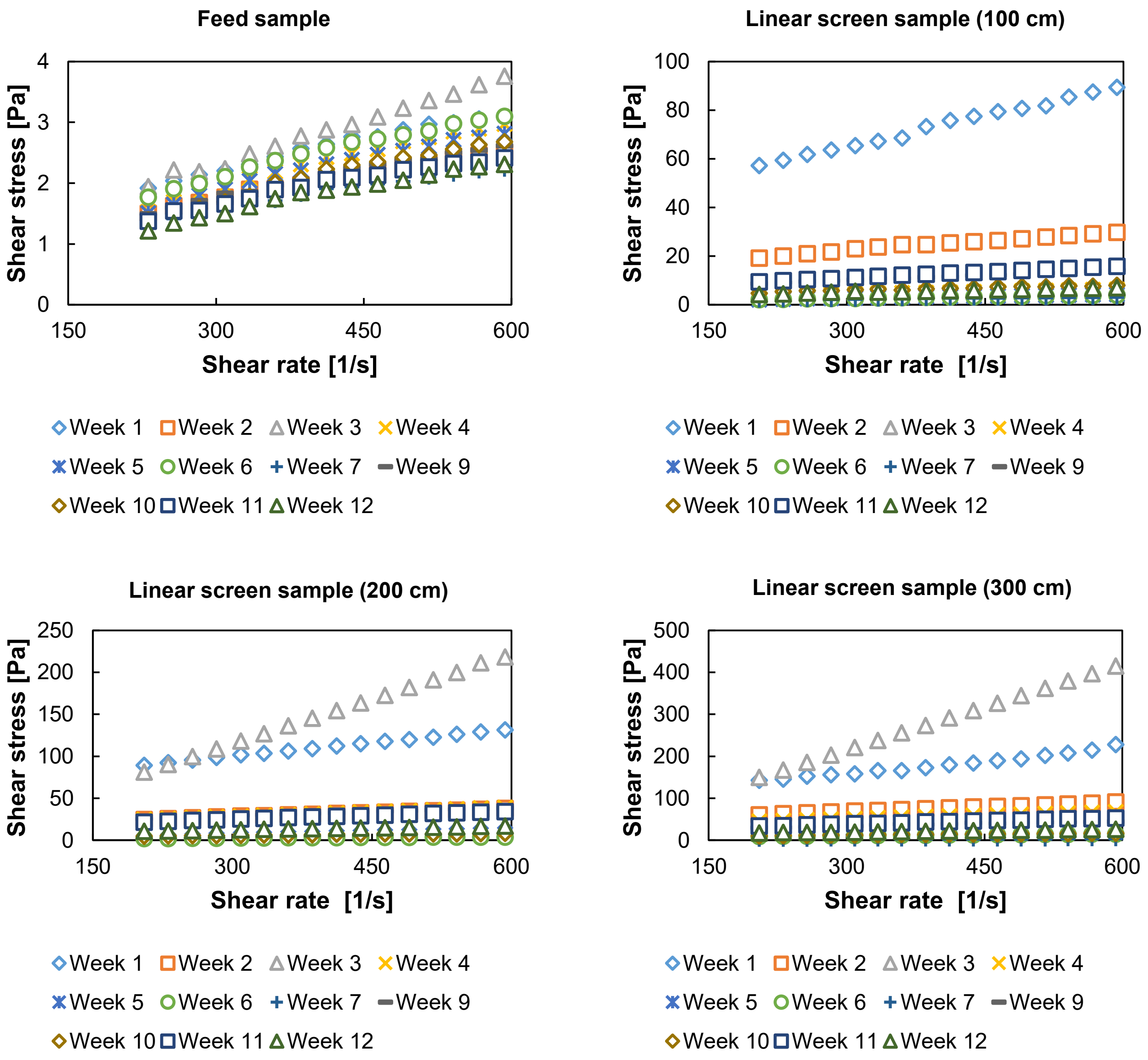
4.4.4 Plant M flow curves

The flow curves for Plant M are presented in Figure 4.10 for the feed sludge before polymer conditioning and the samples on the linear screen at 100 cm, 200 cm, and 300 cm after the sludge conditioning. The week 8 data is not available due to operational breakdown which occurred at the plant.

The shear stress was increasing with the shear rate increase for all the flow curves shown in Figure 4.10. Sludge feed samples have low shear stresses, for the samples on the linear screen the increase of shear stress with shear rate is evident for week 1 and week 2 at 100 cm samples. However; there is an evident increase in the shear stresses for week 1 and week 3 for both 200 cm, and 300 cm samples. With the Bingham model being used to fit the data, the coefficient of determination (R^2) was found to be above 0.95 for all the sludge samples tested which indicate that the data fitted model well. The Bingham yield stress and Bingham viscosity model parameters for all the tested samples at Plant M are summarised in Table 4.13.

Table 4.13: Summary of Bingham parameters range at Plant M over 12-week

Sample	Bingham yield stress [Pa]	Bingham viscosity [Pa.s]
Feed	0.6 - 1.21	0.0025 - 0.0049
100 cm	1.22 - 40.08	0.0046 - 0.083
200 cm	1.01 - 67.55	0.0086 - 0.355
300 cm	9.3 - 96.24	0.206 - 0.683


Feed sample

Linear screen sample (100 cm)

Linear screen sample (200 cm)

Linear screen sample (300 cm)

Figure 4.10: Plant M flow curves over the twelve-week experimental duration

4.5 Comparison of rheological properties

A comparison of the weekly averages for yield stress and viscosity values obtained from flow curves for feed sample and from the linear screen samples are shown in Figure 4.11 to Figure 4.18. The yield stress and viscosity axes are plotted on a log-scale for a better presentation of the data. Table 4.14 to Table 4.21 shows the average values, standard deviations and the CV of the rheological properties of each plant and its sampling points. These values were calculated to quantify the variability of rheological properties. Detailed results for yield stress and viscosity can be found in Appendix A Bingham parameters. In Figure 4.11 and Figure 4.12 the variability of the feed rheological properties can be seen, for Plant M having a yield stress CV of ±21% and viscosity CV of ±19%, this variation was not much compared to Plant L with yield stress CV ±40% and viscosity CV of ±27% and Plant J with yield stress CV of ±164% and viscosity CV of ±50% as shown in Table 4.14 and Table 4.15. However, the effect of sludge thickening prior to dewatering at Plant K plant is evident as its feed has higher rheological properties, but not only high rheological properties also with little variability having the yield stress CV of ±9% and viscosity CV of ±7%.

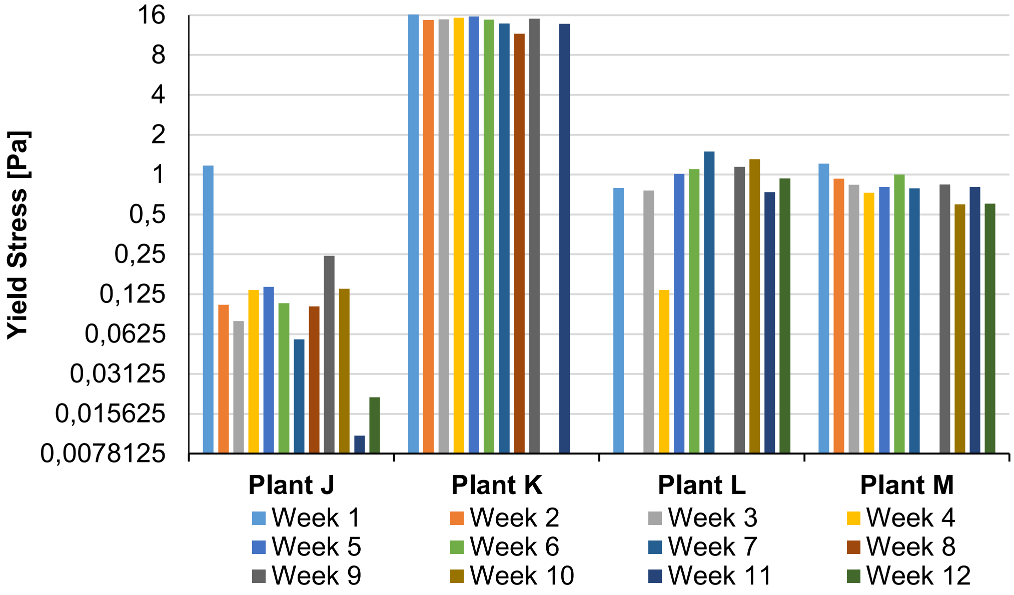


Figure 4.11: Comparison of yield stress for sludge feed samples at various WWTPs

Table 4.14: Comparison of yield stress average, standard deviation and coefficient of variance for sludge feed samples at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.19	14.61	0.94	0.83
SD	±0.32	±1.34	±0.37	±0.17
CV	±164%	±9%	±40%	±21%

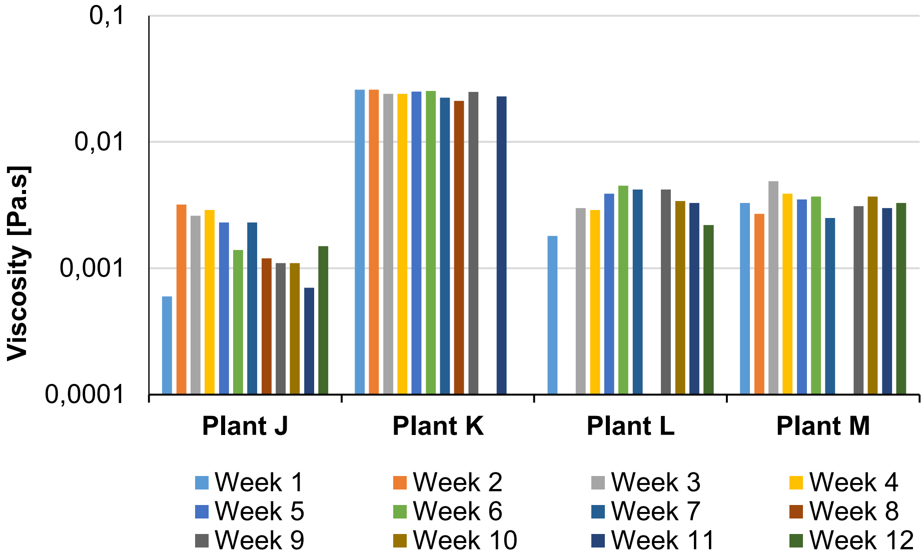


Figure 4.12: Comparison of viscosity for sludge feed samples at various WWTPs

Table 4.15: Comparison of viscosity average, standard deviation and coefficient of variance for sludge feed samples at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.0017	0.024	0.0033	0.0034
SD	±0.00088	±0.0016	±0.00089	±0.00065
CV	±50%	±7%	±27%	±19%

In Figure 4.13 to Figure 4.18 and Table 4.16 to Table 4.21 the variability of yield stress and viscosity values on the linear screen samples is evident for all the plants. With Plant K having higher rheological properties on the linear screen compared to other plants. The variation of rheological properties on the linear screen may be due to a combination of process parameters and/or solids concentration at this point. The Effect of solids concentration on rheological properties and the effect of process parameters on the rheological properties are evaluated in section 4.6 and section 4.7 respectively.

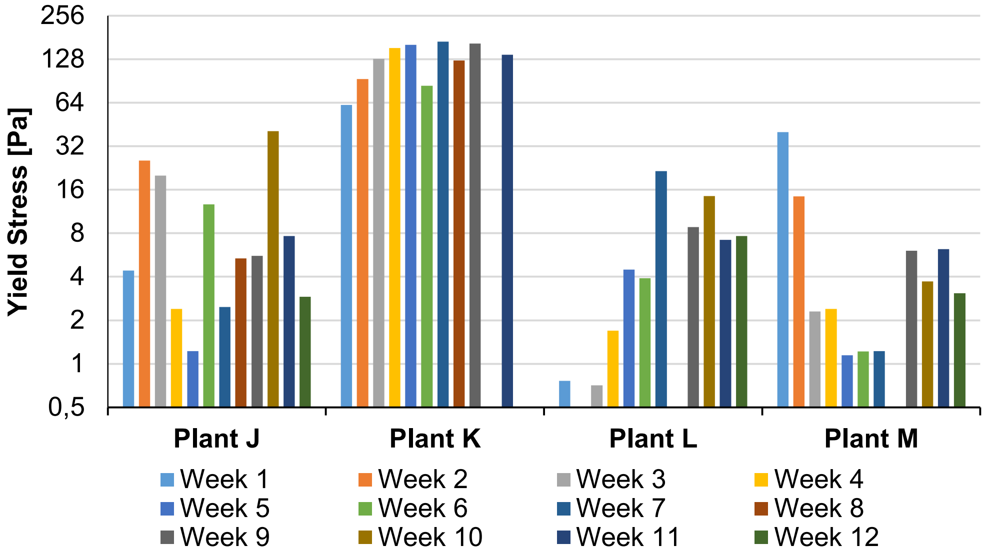


Figure 4.13: Comparison of yield stress for samples at 100 cm on the linear screen at various WWTPs

Table 4.16: Comparison of yield stress average, standard deviation and coefficient of variance for samples at 100 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	10.92	127.55	7.12	7.44
SD	±12.07	±36.92	±6.61	±11.49
CV	±111%	±29%	±93%	±154%

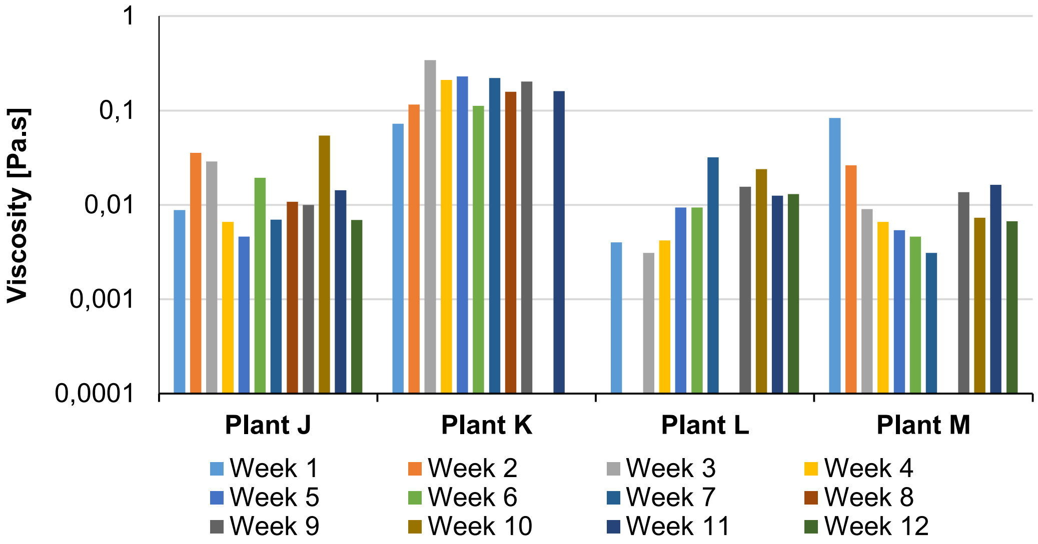


Figure 4.14: Comparison of viscosity for samples at 100 cm on the linear screen at various WWTPs

Table 4.17: Comparison of viscosity average, standard deviation and coefficient of variance for samples at 100 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.017	0.18	0.013	0.017
SD	±0.015	±0.077	±0.0092	±0.023
CV	±87%	±42%	±73%	±140%

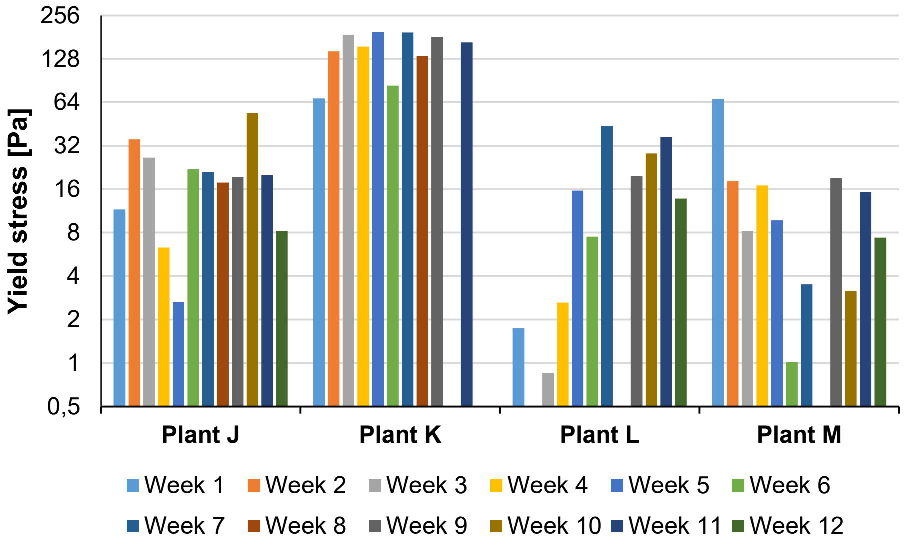


Figure 4.15: Comparison of yield stress for samples at 200 cm on the linear screen at various WWTPs

Table 4.18: Comparison of yield stress average, standard deviation and coefficient of variance for samples at 200 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	20.40	151.37	17.09	15.46
SD	±13.91	±45.18	±15.12	±18.41
CV	±68%	±30%	±88%	±119%

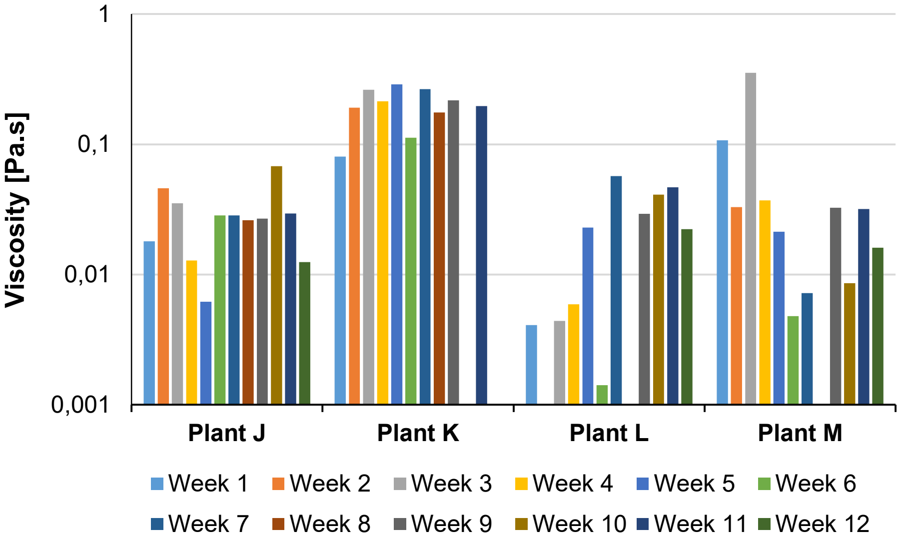


Figure 4.16: Comparison of viscosity for samples at 200 cm on the linear screen at various WWTPs

Table 4.19: Comparison of viscosity average, standard deviation and coefficient of variance for samples at 200 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.028	0.20	0.024	0.06
SD	±0.017	±0.066	±0.02	±0.10
CV	±59%	±33%	±84%	±171%

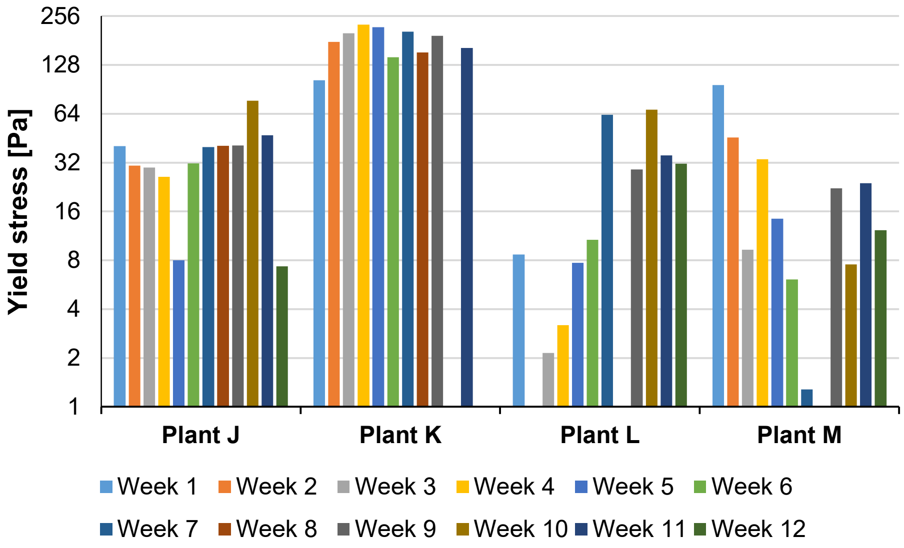


Figure 4.17: Comparison of yield stress for samples at 300 cm on the linear screen at various WWTPs

Table 4.20: Comparison of yield stress average, standard deviation and coefficient of variance for samples at 300 cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	35.01	178.44	25.93	24.77
SD	±18.29	±38.50	±24.07	±27.07
CV	±52%	±22%	±93%	±109%

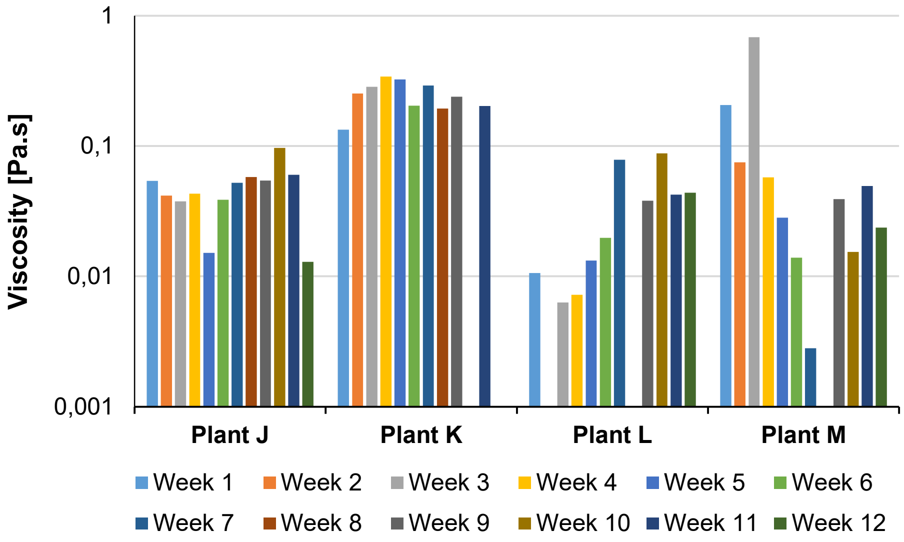


Figure 4.18: Comparison of viscosity for samples at 300 cm on the linear screen at various WWTPs

Table 4.21: Comparison of viscosity average, standard deviation and coefficient of variance for samples at 300cm on the linear screen at various WWTPs

	Plant J	Plant K	Plant L	Plant M
Average	0.047	0.25	0.024	0.11
SD	±0.022	0.065	0.020	0.20
CV	±47%	±26%	±84%	±183%

4.6 Effect of solids concentration on rheological properties

The solids concentration is acknowledged as being a factor strongly affecting sludge rheology (Tixier *et al*., 2003; Monteiro, 1997 & Slatter, 1997). Therefore, it was of the interest to see how the solids concentration affects the rheological properties of the sludge in this study. The data presented in Figure 4.19 and Figure 4.21 shows how the yield stress and viscosity varied with the solids concentration of the tested sludge at different sampling points. Figure 4.20 and Figure 4.22 shows the correlation of the combined data for all the sampling points' rheological properties with solids concentration. Both yield stress and viscosity increased with the increase in solids concentration for feed and linear screen samples.

Many researchers have studied the relationship between yield stress and solids concentration or viscosity and solids concentration, and have described this relationship as being exponential (Tixier *et al*., 2003; Sozanski *et al*., 1997; Sanin, 2002; Guibaud *et al*., 2004). Tixier *et al*. (2003), stated that the yield stress or viscosity relationship with solids concentration is an exponential or power law type.

In this study, a comparison of the exponential and power law models was done to see which model best described the relationship between the yield stress or viscosity with solids concentration. Root mean squared error (RMSE), the coefficient of determination (R^2 adjusted) and Akaike information criterion (AIC) were the techniques used to determine the best model for this set of data. The best model was selected based on having a; low RMSE, high R^2 adjusted and low AIC. The comparison of the exponential and power law is given in Table 4.22 and Table 4.23 for viscosity and yield stress respectively.

For the viscosity plots, the power law and exponential models appear to fit the data well for all the samples as can be seen in Figure 4.19 and Figure 4.20. By referring Table 4.22, it can be seen that the model selection criteria values for both exponential and power law models were quite close to each other for all the samples, which proves to be the reason why researchers choose either model when they describe the relationship between the viscosity and the solids concentration. The power law and exponential models fitted the data well on all the samples, as suggested by high adjusted R^2 values above 0.834. However, these sets of data were best described by the power law for having lower RMSE and AIC values.

For combined data, the relationship between the viscosity and the solids concentration was described best by the power law having a; lower RMSE; higher adjusted R^2 and lower AIC value than the exponential model.

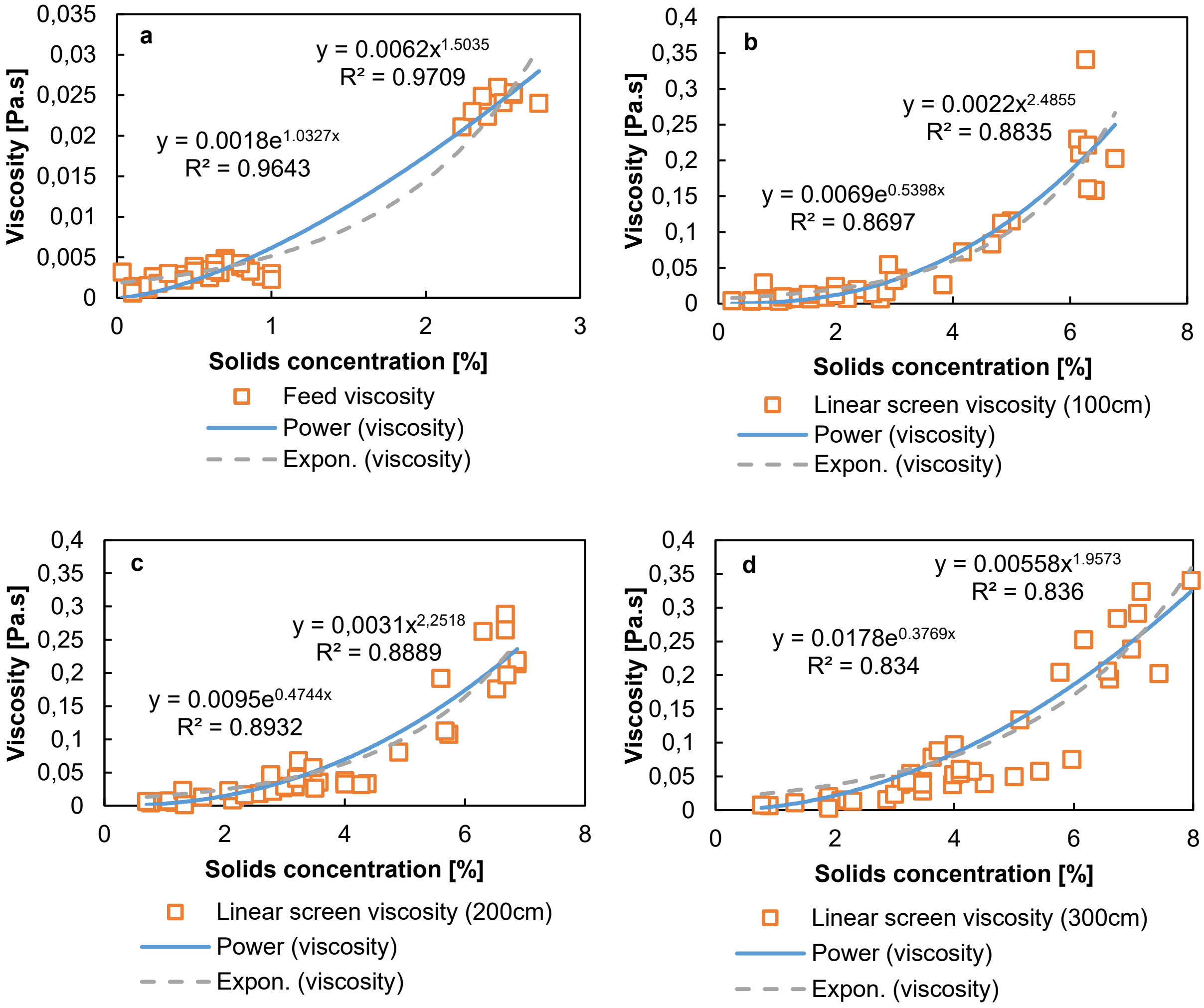


Figure 4.19: Correlation of the Bingham viscosity with solids concentration (a) for feed sludge (b) at 100 cm from the start of the linear screen (c) 200 cm from the start of the linear screen (d) 300 cm from the start of the linear screen

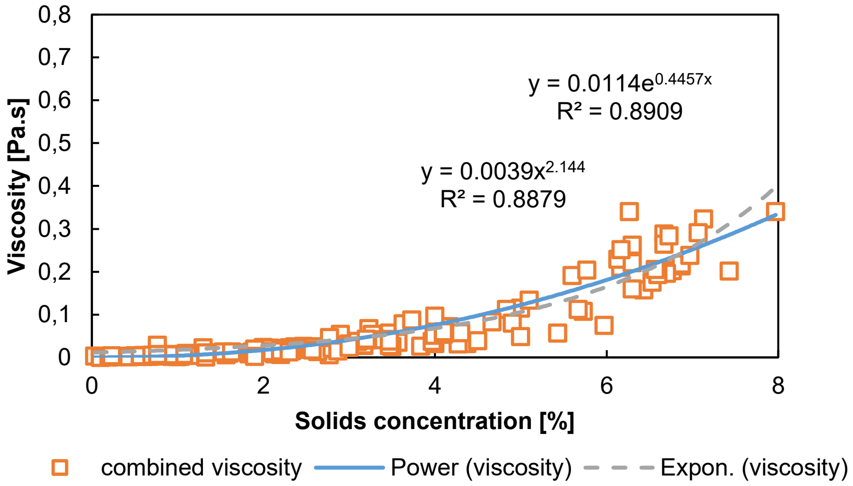


Figure 4.20: Combined correlation for feed and samples on the linear screen viscosity with solids concentration for all the WTTPs

Table 4.22: Comparison of model selection criteria values for viscosity

	Feed viscosity		
Model	RMSE	R^2adj	AIC
Power law	0.0016	0.9702	-551.8
Exponential	0.0018	0.9634	-542.9
	Viscosity at 100 cm		
Model	RMSE	R^2adj	AIC
Power law	0.0279	0.8807	-305.4
Exponential	0.0296	0.8665	-300.6
	Viscosity at 200 cm		
Model	RMSE	R^2adj	AIC
Power law	0.0277	0.8862	-306.6
Exponential	0.0271	0.8906	-308.3
	Viscosity at 300 cm		
Model	RMSE	R^2adj	AIC
Power law	0.0396	0.8324	-275.7
Exponential	0.0399	0.8299	-275.0
	Combined viscosity		
Model	RMSE	R^2adj	AIC
Power law	0.0271	0.8872	-1238.7
Exponential	0.0284	0.8763	-1222.9

For the yield stress plots, the power law and exponential models also appear to fit the data well for all the samples as can be seen in Figure 4.21 and Figure 4.22. By referring to Table 4.23, it can be seen that the model selection criteria values for both exponential and power law models were quite close to each other for all the samples, showing why researchers choose either model when they describe the relationship between the yield stress and the solids concentration. The power law and exponential models fitted the data well from the feed samples and the samples from the start of the BFP, as suggested by high adjusted R^2 values above 0.83. However, the relationship between yield stress and solids concentration for these sets of data were best described by the power law for having lower RMSE and AIC values. Also for combined data, the relationship between the yield stress and the solids concentration was described best by the power law having a; lower RMSE; higher adjusted R^2 and lower AIC value than the exponential model.

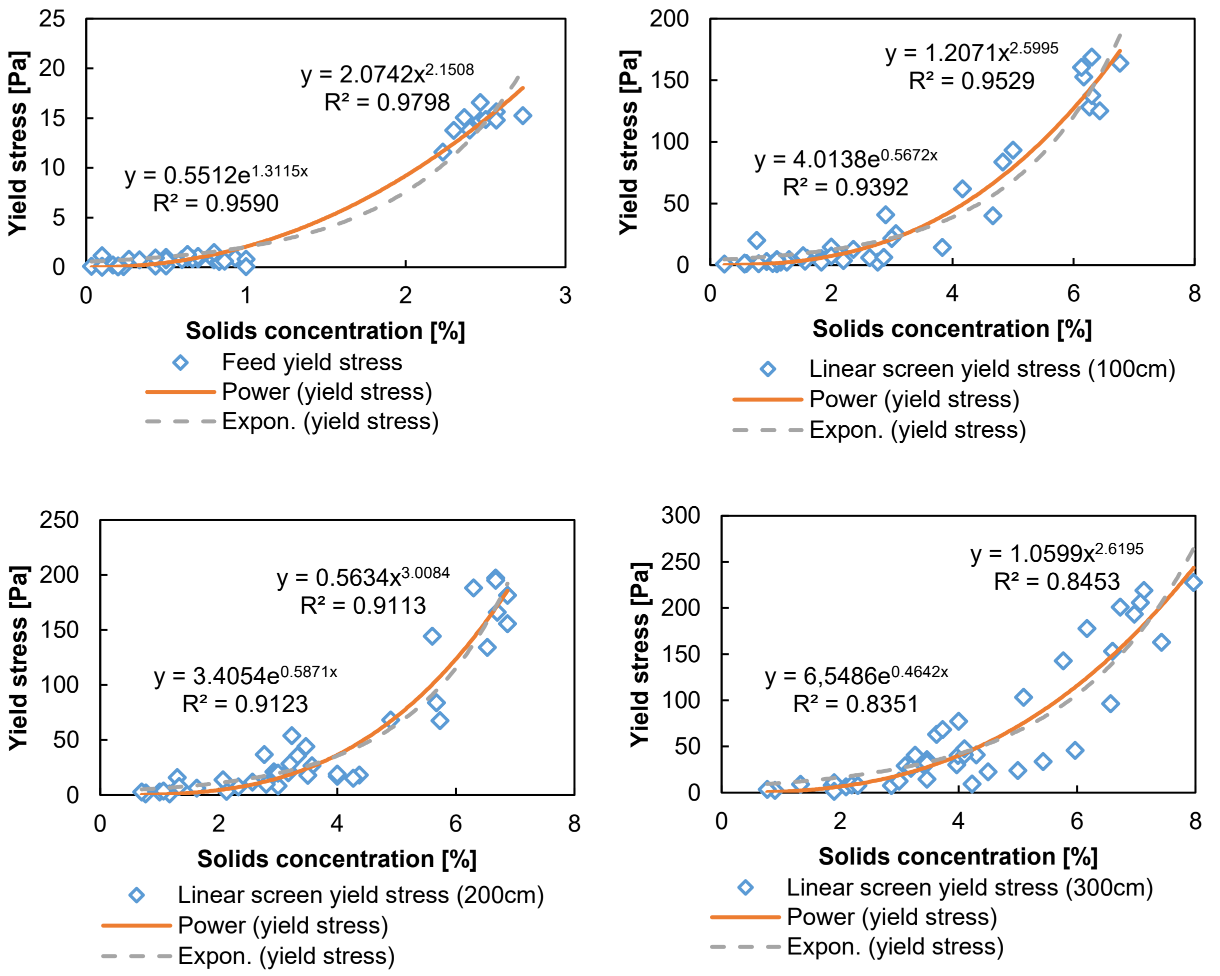


Figure 4.21: Correlation of the yield stress with solids concentration (a) for feed sludge (b) at 100 cm from the start of the linear screen (c) 200 cm from the start of the linear screen (d) 300 cm from the start of the linear screen

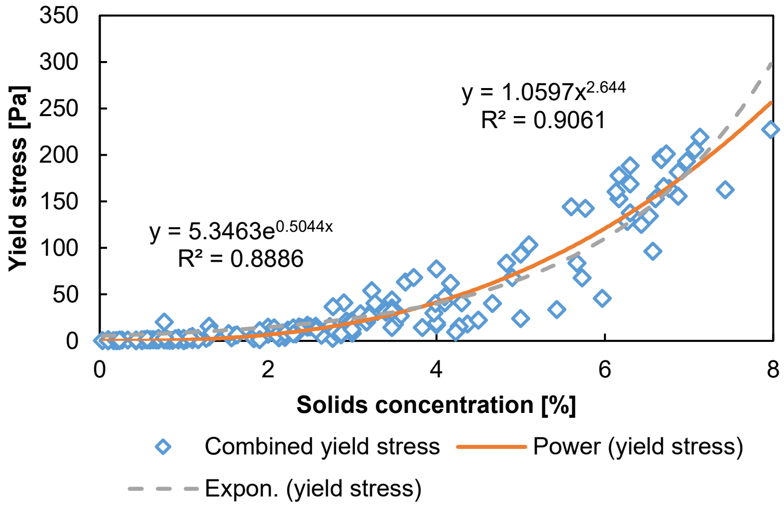


Figure 4.22: Combined correlation for feed and samples on the linear screen yield stress with solids concentration for all the WTTPs

Table 4.23: Comparison of model selection criteria values for yield stress

	Feed yield stress		
Model	RMSE	R^2adj	AIC
Power law	0.866	0.9793	-10.1
Exponential	1.234	0.9580	20.3
	Yield stress at 100 cm		
Model	RMSE	R^2adj	AIC
Power law	11.9	0.9517	215.6
Exponential	13.6	0.9377	226.6
	Yield stress at 200 cm		
Model	RMSE	R^2adj	AIC
Power law	18.8	0.9092	254.5
Exponential	18.7	0.9102	254.0
	Yield stress at 300 cm		
Model	RMSE	R^2adj	AIC
Power law	27.6	0.841544	287.6
Exponential	28.5	0.831097	290.4
	Combined yield stress		
Model	RMSE	R^2adj	AIC
Power law	17.9	0.9055	994.7
Exponential	19.4	0.8879	1022.1

Based on the analysis made in this section, it was evident that the relationship between the sludge rheological properties and solids concentration can be described by both the power law and exponential models as also reported by Tixier *et al*. (2003); Sozanski *et al*. (1997); Sanin (2002) and Guibaud *et al*. (2004). The power law model fits the data slightly better.

4.7 Effect of process parameters on the rheological properties

It was of interest to evaluate how the yield stress changes with a combination of process parameters such as sludge feeding rate, polymer dosing rate, and the linear screen belt speed. A product of sludge flow rate, polymer dosing and belt speed was then plotted against the measured yield stress at 100 cm. The data presented in Figure 4.23 shows how the yield stress varied with the combination of process parameters of the BFP. Plant K is plotted on a separate graph due to small values of the product of process parameters and for better presentation.

It was observed that Plant K's yield stress (at 100 cm) values were very sensitive to change in process parameters without any obvious trend. However; for Plant J, Plant L and Plant M the increase in the product of process parameters the seemed to decrease yield stress values. It was also observed that Plant J and Plant L trends are close to each other, having the same dewatering systems delivering the same solids concentration.

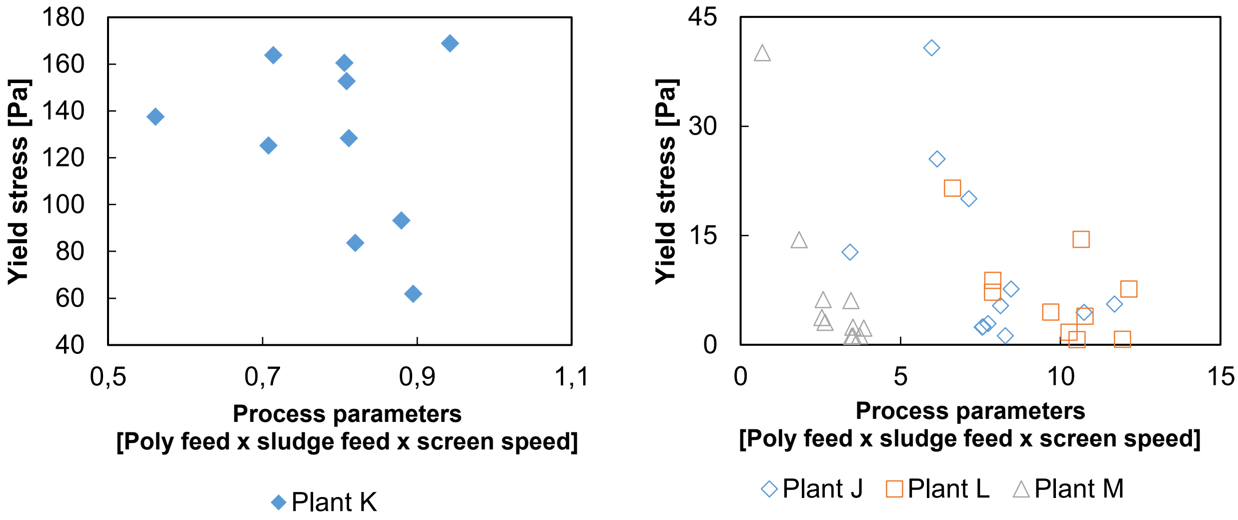


Figure 4.23: Correlation of linear screen yield stresses with process parameters per plant

4.8 Conclusion

Rheological characterisation of activated sludge was investigated at four WWTPs to determine the variability of process parameters (polymer dosing rate, sludge feed rate, BFP speed and linear screen speed), solids concentration and rheological properties. These WWTPs had different BFP configurations. Plant J, L and M used only linear screens while Plant K had a sludge thickener prior to BFP dewatering. Plants J and L had exactly the same BFP systems. It was shown that Plant K had low process parameter variability (CV) with a maximum of 8% compared to other WWTPs where the CV for operational parameters ranged from 14% to 33%.

From the results it was evident that the sludge solids concentration for both unconditioned and conditioned sludges for WWTPs without thickeners had high variability. However, at Plant K, the effect of sludge thickening prior to dewatering was effective in producing sludge with consistent sludge solids concentration and rheological properties before sludge conditioning.

Sludge rheological properties were obtained by fitting a Bingham model on the shear stress-shear rate flow curves and found to be capable of characterising the sludge from all the plants. The coefficient of determination for the Bingham model was above 0.90. It was shown that Plant K feed sludge had high rheological properties and low variability (CV) with a maximum of ±9% compared to other plants where the CV for feed sludge rheological properties ranged from ±19% to ±164%. It was shown that once the polymer was added to sludge a high variability of rheological properties on the BFP ranged from 22% to 183%.

Despite the variation in rheological parameters obtained and the fact that BFPs from three manufacturers were evaluated some with and others without prior thickening of sludge, these parameters collapsed onto a single curve for each measurement position when presented as a function of solids concentration. This proves that the relationship between the rheological parameters and the solids concentration is similar across all these treatment plants. A comparison between power law and exponential model for describing the relationship between rheological properties and solids concentration was done based on three different statistical techniques. It was shown that the relationship between the sludge rheological properties and solids concentration was better described by the power law model. However, from a practical perspective either model could be used over the range of data tested.

However, when the rheological parameters were presented as a function of the BFP operating conditions, the effect of different dewatering systems was evident as it delivered different solids concentrations at the same sampling points. The yield stresses plotted relates to the specific solids concentration measured. This work showed that the rheological properties after sludge conditioning were only dependent on sludge solids concentration.

Chapter 5 Effect of rheological properties on the belt filter press performance

5.1 Introduction

As far as can be ascertained there is no scientific literature to demonstrate optimisation of belt filter presses by rheological properties. In such a case with many variables a designed experiments method is advantageous to use. The Box-Behnken design was utilised in this study. The main advantages of the Box-Behnken design are that it only requires three levels of each factor and fewer experimental runs. The purpose of the present work was to investigate the possibility of using a statistical experimental design approach to optimise the belt filter press sludge dewatering process in Plant K. The initial solids concentration of sludge was 2.9 ±0.22% by mass and the belt speed 100% corresponds to 0.062 m/s. In this chapter the following topics are evaluated and discussed:

- The effect of the belt filter press operating parameters (polymer concentration, polymer dosing, sludge flow rate and belt speed) on the rheological properties (viscosity and yield stress)
- The effect of operating parameters on the cake solids concentration (CSC).
- The effect of operating parameters on the filtrate suspended solids (FSS)
- The effect of operating parameters on the solids capture.

The relationship between rheological properties and CSC, the relationship between rheological properties and filtrate suspended solids (FSS) and, the relationship between rheological properties and solids capture are also evaluated. The factorial trial responses for the experimental matrix presented in Table 3.3 are given in Table 5.1.

Table 5.1 Factorial trial measured response

Std	*Run*	*Cake solids concentration*	*Filtrate solids*	*100 cm yield stress*	*100 cm viscosity*	*Solids recovery*
		g/L	g/L	Pa	Pa.s	%
12	1	139	0.8	120.49	0.1512	97.52
15	2	151.3	12.73	9.89	0.0177	60.83
11	3	161.7	1.73	70.42	0.0887	94.59
27	4	138.7	0.71	109.63	0.1291	97.71
16	5	139.3	2.86	83.78	0.1219	90.77
23	6	122.3	0.78	146.94	0.1796	97.43
22	7	143	0.75	131.21	0.1507	97.58
7	8	153	0.82	152.63	0.1858	97.40
8	9	130.5	7.77	18.06	0.0272	74.94
25	10	149	0.85	147.45	0.172	97.34
26	11	146	0.77	133.33	0.1604	97.52
2	12	148	1.02	89.57	0.1017	96.60
6	13	114.7	9.17	13.11	0.0216	70.89
21	14	144	2.33	123.43	0.1351	92.15
24	15	132	0.48	140.02	0.0941	98.32
1	16	132.5	5.02	42.59	0.1049	81.53
18	17	149	1.37	130.92	0.1527	94.96
3	18	133	1.28	77.18	0.0845	95.30
14	19	137.3	2.19	132.92	0.159	91.81
10	20	139.7	0.73	155.76	0.1677	97.27
28	21	133	0.65	90.30	0.099	97.60
9	22	135	2.48	128.05	0.1486	90.76
13	23	130	0.5	131.80	0.1353	98.14
17	24	133.67	0.6	154.05	0.1728	97.75
20	25	125.33	6.1	89.83	0.109	77.15
29	26	129	0.7	139.71	0.1692	97.39
5	27	137	0.3	122.19	0.1507	98.88
4	28	138.33	0.4	117.19	0.1523	98.52
19	29	135.33	11.3	7.97	0.0142	57.99

5.2 Effect of process parameters on the sludge rheological properties

In the Box–Behnken design, 29 experimental observations were undertaken at randomly in order to determine the relationship between the belt press operating parameters and sludge rheological properties (yield stress and viscosity) at 100 cm from the start of belt press. Before 100 cm the sludge proved to be difficult to measure in the rheometer and therefore this was the first point where the sludge could be measured. It was because before 100 cm the sludge flocs and water separates as shear force is applied. For each experimental run, the shear stress and shear rate of the sludge samples were measured using the MRC-51 rheometer. From resulting flow curves the Bingham model was fitted to obtain the yield stress and viscosity.

5.2.1 Development of sludge yield stress model

Even though the model being developed is empirical in nature, there is no prior understanding about the nature of the relationship between the process parameters and the yield stress. As a result of analysing the measured responses using the Design-Expert software, the significance test for the regression models and the significance test of individual model coefficients were determined by the same statistical software package for all responses. A stepwise selection procedure (stepwise backwards) was used to deselect terms that do not make a contribution to the model. Polymer dosing (B) and the belt speed (D) are the process parameters that did not make a contribution to the model or their contribution was not significant. The resulting ANOVA Table 5.2 for the yield stress quadratic model outlines the analysis of variance for this response and shows the significant model terms affecting the yield stress at 100 cm. This table also demonstrates additional adequacy measures, for example, R^2 and adjusted R^2. The R^2 values indicate the degree of fit and are defined as the ratio of the explained variation to the total variation. It is suggested that a good model fit should be an R^2 of at least 0.8. However; in this study these adequacy measures were found to be below 0.8 as shown in Table 5.2, suggesting that this quadratic model was only a reasonable fit for this data. The model was significant, as indicated by the very low probability value of less than 0.05. A p-value that is lower than 0.05 suggests that the model is statistically significant at the 5% level of significance.

Table 5.2 ANOVA for yield stress quadratic model

ANOVA for Response Surface modified quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	42707.9	4	10677	14.91	2.98E-06	significant
A	4162.8	1	4162.7	2.02	0.024	
C	30186	1	30186	27.43	1.03E-06	
AC	2756	1	2756	1.32	0.06	
C^2	5603.2	1	5603.2	2.79	0.01	
Residual	17190.8	24	716.3			
Corrected Total	59898.6	28				

R^2 =0.71; adjusted R^2 = 0.67

A represents the polymer concentration, C the sludge flow rate, AC is the interaction between polymer concentration and sludge flow rate, C^2 is the quadratic effect of sludge flow rate and $\tau_{100\ \mathrm{cm}}$ is the yield stress at 100 cm. The following quadratic model was found to represent the relationship between the yield stress at 100 cm from the start of the belt press and the input variables. The final model terms of coded factors are presented in Equation 5.1 and Equation 5.2 for uncoded (actual) factors.

$$\tau_{100\ \mathrm{cm}} = 115.5 + 18.6^{*}\mathrm{A} - 50.15^{*}\mathrm{C} + 26.29^{*}\mathrm{AC} - 28.22\ ^{*}\mathrm{C}^2 \qquad \text{Equation 5.1}$$

$$\tau_{100\ \mathrm{cm}} = 312.55 - 1202.43\mathrm{A} - 2.41^{*}\mathrm{C} + 105^{*}\mathrm{AC} - 1.13\ ^{*}\mathrm{C}^2 \qquad \text{Equation 5.2}$$

These models can be used to predict the yield stress within the range of the factorial trial, by substituting the values of A and C or their -1 to 1 codes as shown in Table 3.2. The actual units for parameter AC and C^2 are m^3/hr and m^6/hr^2 in Equation 5.2 respectively.

It is important to note that the coded equation (Equation 5.1) is useful for identifying the relative impact of the factors by comparing the factor coefficients. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

In Equation 5.1 a positive sign before a term indicates an increasing effect, while a negative sign indicates a decreasing effect on yield stress. The presence of the binary term in Equation 5.1 indicates that the yield stress depends on both single and mixture variables. The binary term shows that there is an increasing effect between factors A (polymer concentration) and C (sludge flow rate) on the yield stress.

5.2.2 Model validation sludge yield stress

To obtain an adequate model, a model validation is important. The yield stress model validation was evaluated by plotting a normal probability (%) against the internally studentised residuals shown in Figure 5.1. From Figure 5.1 it can be seen that the relationship between normal probability and internally studentised residuals fitted well linearly. This linear fit means that no response transformation was necessary and that there was no specious problem with the normality of the data.

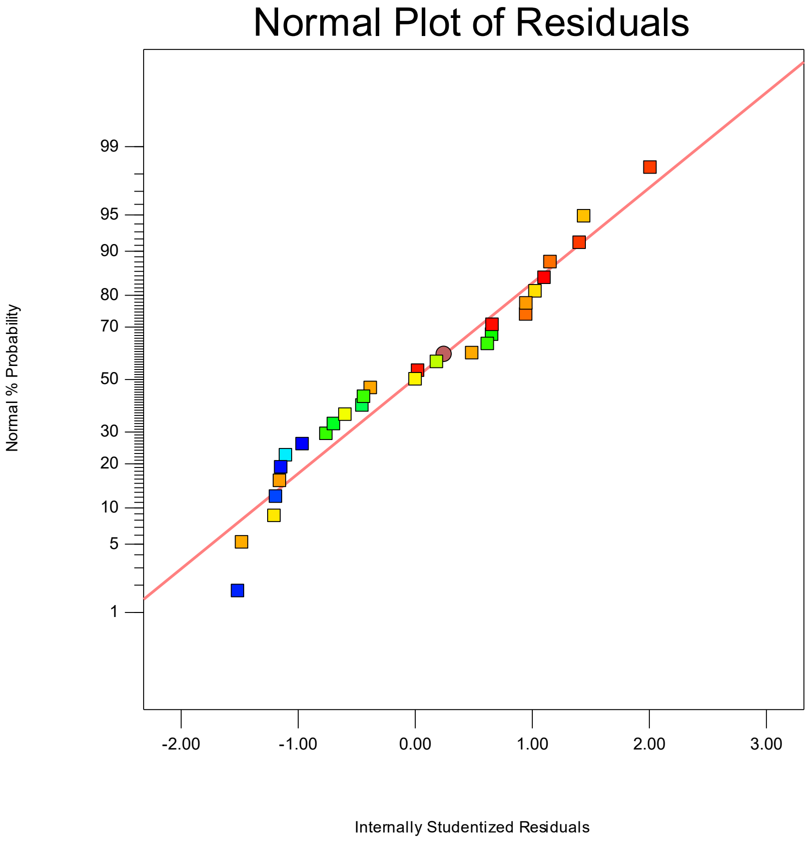


Figure 5.1 Normal plot showing the link between normal probability (%) and internally studentised residuals for yield stress

The validation of the yield stress model was assessed by evaluating the relationship between the actual and the predicted values of the yield stress as shown Figure 5.2. This figure indicates that the developed model was adequate for prediction of the yield stress since the predicted values were relatively close to the observed yield stress values. This was also explained by the R^2 value of 0.71, indicating that the model explains 71% of the variation.

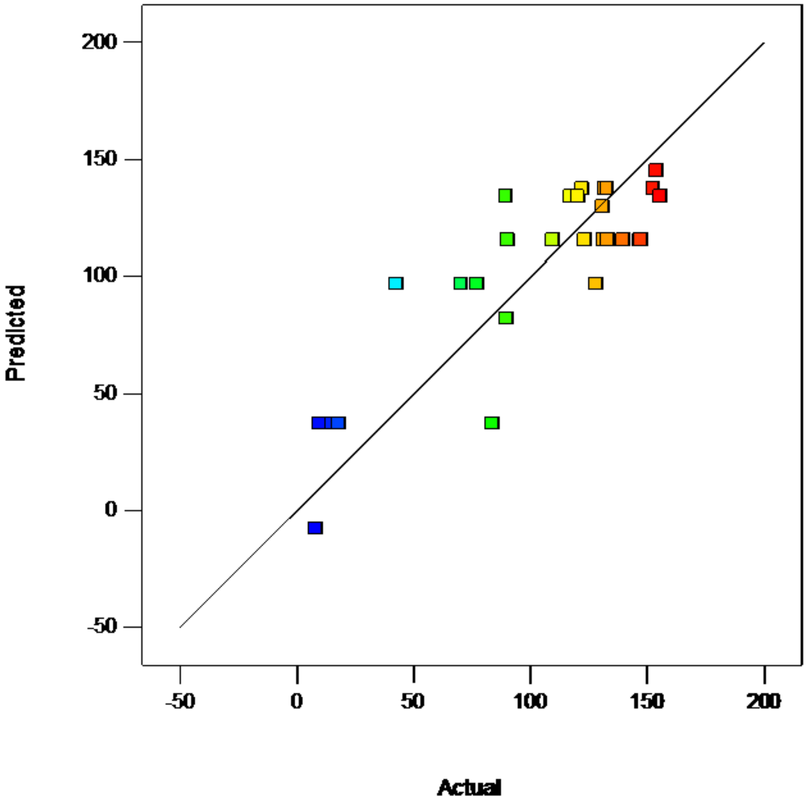


Figure 5.2 Predicted yield stress values vs actual (experimental) yield stress values

5.2.3 Effect of process parameters on the yield stress

The yield stress at 100 cm is directly related to the process parameters investigated, either as a main or as part of an interaction effect, as stated earlier. It has already been shown that polymer dosing and belt press speed do not have a significant effect on the yield stress, therefore these two factors are not discussed. The reason for predicting the yield stress is to develop a model, to aid in the selection of an appropriate range for process optimisation.

The primary factor most affecting the yield stress appears to be the sludge flow rate (C). The model indicates that if the sludge flow rate 1 coded unit, then yield stress decreases by 50.56 units. This is because while other factors are kept constant, as a result of sludge flow rate increasing the strength of sludge flocs become weaker and therefore resistance to shear weakens.

The interaction between polymer concentration and the sludge flow rate, parameter AC, was found to be the second most influential factor and the only interaction affecting the yield stress. The model indicates that if this parameter AC, is increased by 1 coded unit, then the yield stress increases by 26.29 units. This effect was higher than polymer concentration alone, thus highlighting the ineffectiveness of evaluating process parameters through isolation.

The polymer concentration had the lowest significant effect on the yield stress. The model shows that if factor A (polymer concentration) is increased by 1 (coded) unit, then $\tau_{100\ \mathrm{cm}}$ is increased by 18.6 units. The polymer concentration had the opposite effect as compared to sludge flow rate.

Figure 5.3 shows a perturbation plot highlighting the effect of polymer concentration and sludge flow rate on the yield stress at 100 cm from start of the belt filter press. The perturbation plot permits to compare the effect of all the factors at a certain point in the design space. This type of plot is like a one factor at a time experimentation and therefore does not show the effect of interactions.

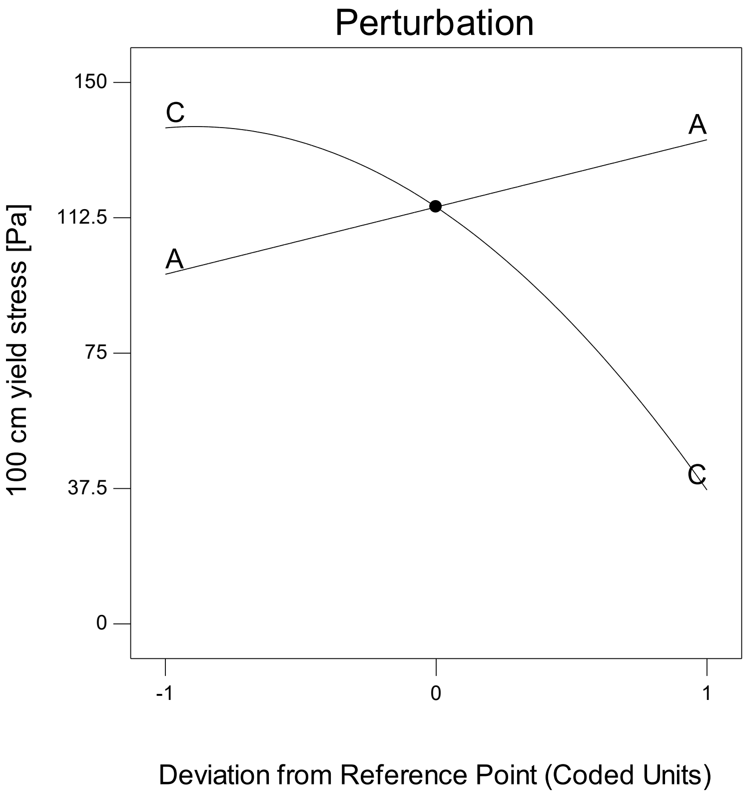


Figure 5.3 Perturbation plot showing the effect of polymer concentration and sludge flow rate on the yield stress

The significant interaction (between the polymer concentration and the sludge flow rate) affecting the yield stress is shown in Figure 5.4. The 3-D and 2-D contour plots are presented in Figure 5.5, and highlight the positive influence of increasing both the polymer concentration and the sludge flow rate. This figure shows that the yield stress increases directly, with an increase in polymer concentration, while it decreases with an increase in the sludge flow rate. At low polymer concentration (0.2%) and high sludge flow rate (20m^3/hr), the yield stress diminished. There was a significant increase in the yield stress to about 80 Pa at high polymer concentration (0.3%) and high sludge flow rate. It was observed at both low polymer concentration and low sludge flow rate that the yield stress was much higher compared to high polymer concentration and high sludge flow rate.

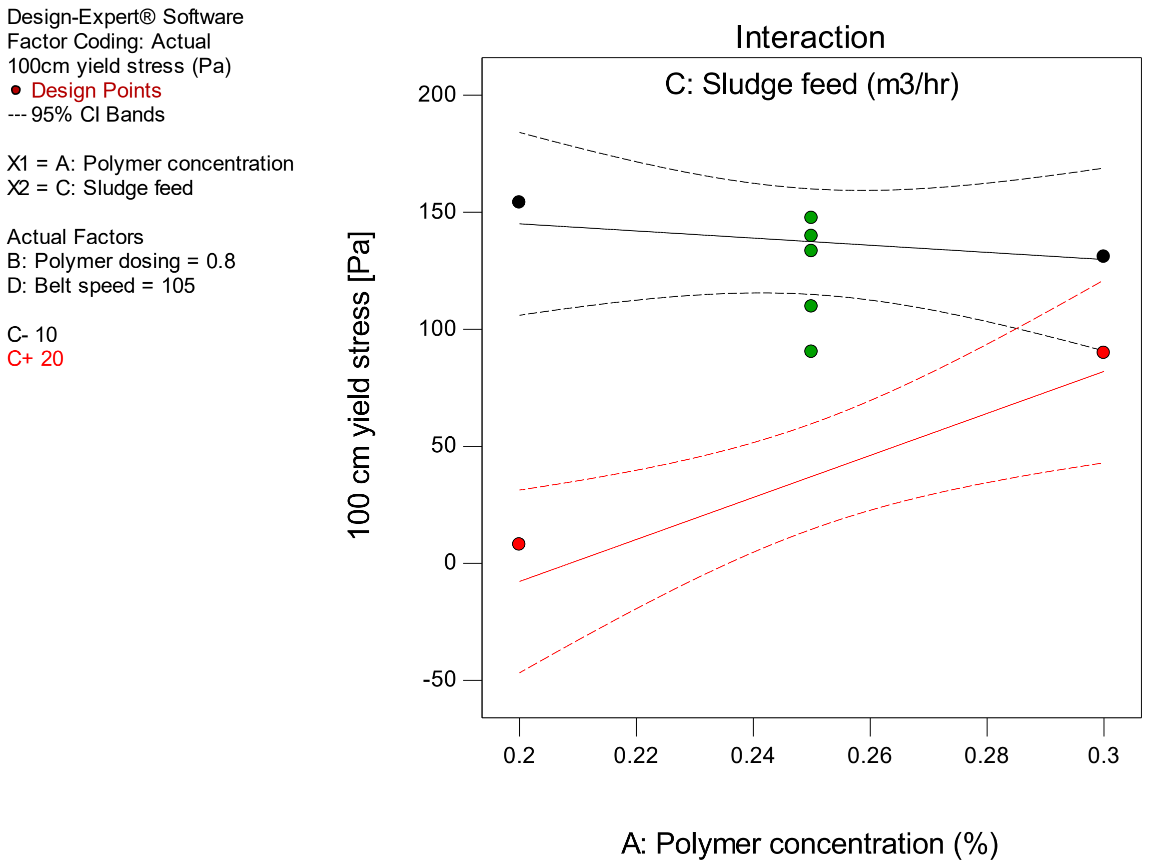


Figure 5.4 Interaction plot showing the most significant interaction effect of polymer concentration and sludge flow rate on the yield stress

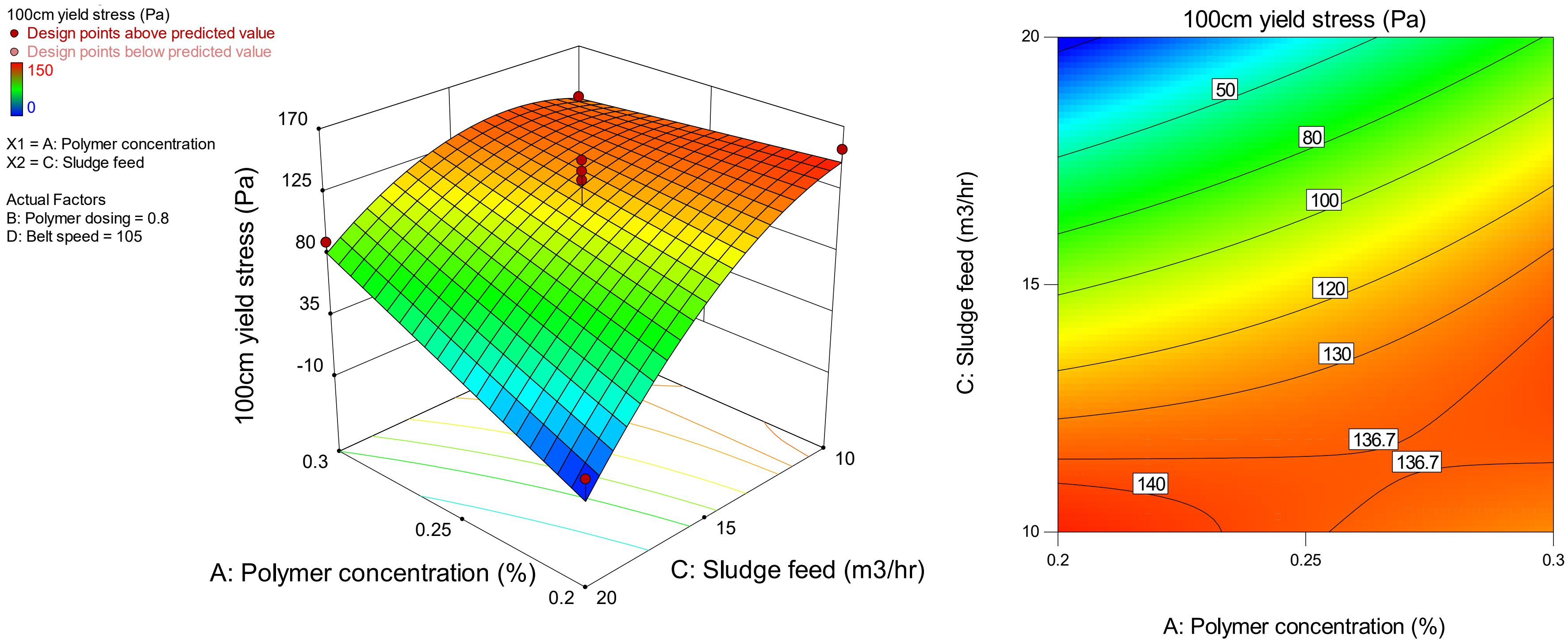


Figure 5.5 3D surface and 2D contour plots showing the effect of polymer concentration and sludge flow rate on the yield stress

5.2.4 Development of sludge viscosity model

As a result of analysing the measured responses (viscosity) using the Design-Expert software V10.0.0, the significance test for the regression models and the significance test of individual model coefficients were determined by the same statistical software package for all responses. Even though the model being developed is empirical in nature, there is no prior understanding about the nature of the relationship between the process parameters and the viscosity. A stepwise selection procedure (stepwise backwards) was used to deselect terms that do not make a contribution to the model (insignificant model terms). Polymer dosing (B) and the belt speed (D) were the process parameters that did not make a contribution to the model or their contribution was not significant and, therefore were excluded. The resulting ANOVA Table 5.3 for the viscosity quadratic model outlines the analysis of variance for this response and shows the significant model terms affecting the viscosity at 100 cm. This table also demonstrates additional adequacy measures, R^2 and adjusted R^2. The model adequacy measures were found to be below 0.8 as shown in Table 5.3, suggesting that this quadratic model was only a reasonable fit for this data. The model was significant, as indicated by the very low probability value of less than 0.05.

Table 5.3 ANOVA for viscosity quadratic model

ANOVA for Response Surface modified quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	0.051	4	0.013	11.32	< 0.0001	significant
A	6.399E-003	1	6.399E-003	5.73	0.0249	
C	0.035	1	0.035	31.00	< 0.0001	
AC	3.301E-003	1	3.301E-003	2.95	0.0986	
C^2	6.242E-003	1	6.242E-003	5.59	0.0265	
Residual	0.027	24	1.117E-003			
Corrected Total	0.077	28				

$R^2 = 0.65$; adjusted $R^2 = 0.60$

The following quadratic models were found to represent the relationship between the sludge viscosity at 100 cm from the start of the belt press and the input variables. The final model terms of coded factors are presented in Equation 5.3 and Equation 5.4 for uncoded (actual) factors.

$$\mu_{100\ \mathrm{cm}} = 0.14 + 0.023^{*}\mathrm{A} - 0.054^{*}\mathrm{C} + 0.029^{*}\mathrm{AC} - 0.03^{*}\mathrm{C}^{2} \qquad \text{Equation 5.3}$$

$$\mu_{100\ \mathrm{cm}} = 0.3439 - 1.2617^{*}\mathrm{A} - 3.7235\mathrm{x}10^{-3*}\mathrm{C} + 0.1149^{*}\mathrm{AC} - 1.1916^{*}\mathrm{C}^{2} \qquad \text{Equation 5.4}$$

A represents the polymer concentration, C the sludge flow rate and $\mu_{100\ \mathrm{cm}}$ is the viscosity at 100 cm. These can be used to predict the viscosity within the range of the factorial trial, by substituting the values of A and C or their -1 to 1 codes as shown in Table 3.2.

In Equation 5.3 a positive sign before a term indicates an increasing effect, while a negative sign indicates a decreasing effect on viscosity. The presence of the binary term in Equation 5.3 indicates that the viscosity depends on both single and mixture variables. The binary term shows that there is an increasing effect between factors A (polymer concentration) and C (sludge flow rate) on the viscosity.

5.2.5 Model validation for sludge viscosity

To obtain an adequate model, a model validation is important. The viscosity model validation was evaluated by plotting a normal probability (%) against the internally studentised residuals shown in Figure 5.6. From Figure 5.6 it can be seen that the relationship between normal probability and internally studentised residuals fitted well linearly. This linear fit means that no response transformation was necessary and that there was no specious problem with the normality of the data.

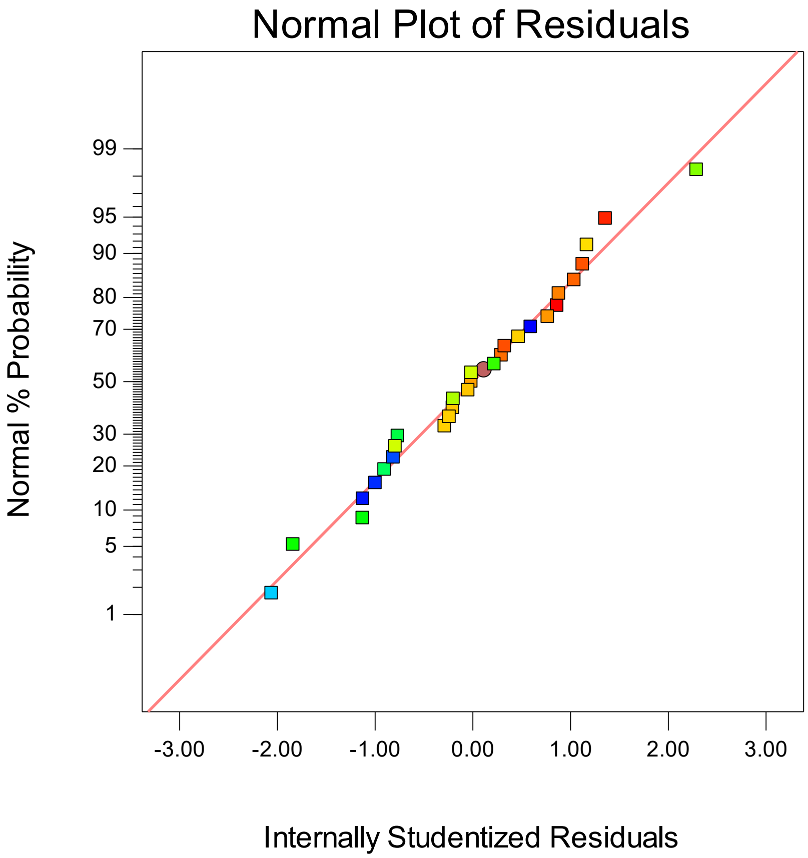


Figure 5.6 Normal plot showing the link between normal probability (%) and internally studentised residuals for viscosity

The validation of the viscosity model was assessed by evaluating the relationship between the actual and the predicted values of the viscosity as shown Figure 5.7. This figure indicates that the developed model was relatively adequate for prediction of the viscosity. This was also confirmed by the R^2 value of 0,65 indicating that the model explains 65% of the variation. This value was lower than compared to that of the yield stress.

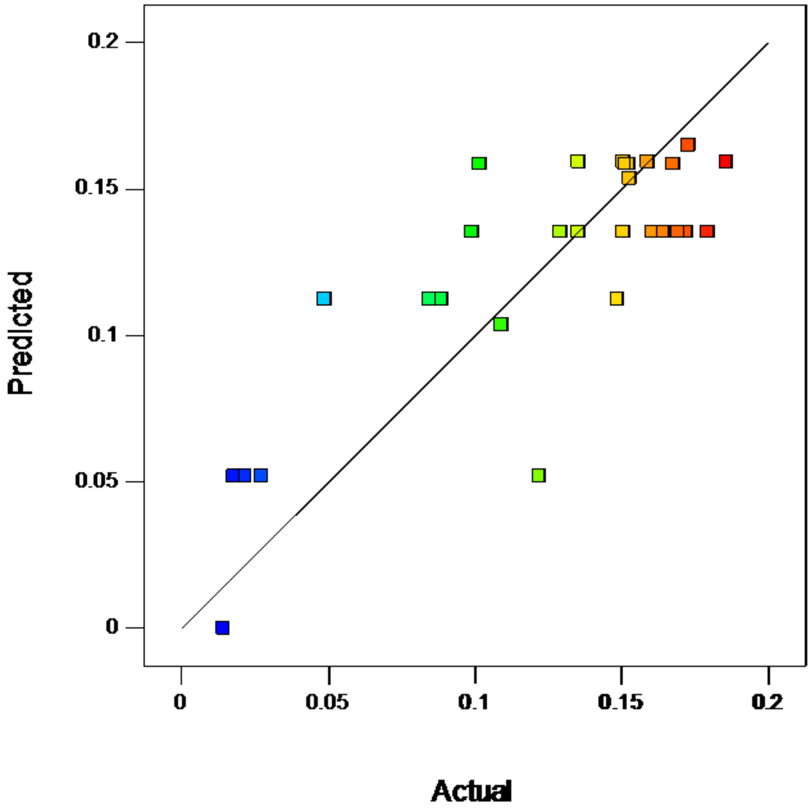


Figure 5.7 Predicted viscosity values vs actual (experimental) viscosity values

5.2.6 Effect of process parameters on the sludge viscosity

The sludge viscosity at 100 cm is directly related to the process parameters investigated, either as a main or as part of an interaction effect. It has already been shown that polymer dosing and belt press speed do not have a significant effect on the viscosity of the sludge, therefore these two factors would not be discussed. The reason for predicting the viscosity is to develop a model, to aid in the selection of an appropriate range for process optimisation or in the prediction of critical belt press performance measures such as the filtrate suspended solids or solids recovery.

The primary factor most affecting the sludge viscosity appeared to be the sludge flow rate (C). The model indicates that if the sludge flow rate 1 coded unit, then the viscosity decreases by 0.054 units. This is because while other factors are kept constant, as a result of sludge flow rate increasing the strength of sludge flocs become weaker and therefore there is less resistance to flow.

The interaction between polymer concentration and the sludge flow rate, parameter AC, was found to be the second most influential factor and being the only interaction affecting the sludge viscosity. The model indicates that if this parameter AC, is increased by 1 coded unit, then sludge viscosity increases by 0.029 units. This effect was higher than polymer concentration alone, thus highlighting the ineffectiveness of evaluating one process parameter at a time.

The polymer concentration had the lowest significant effect on the sludge viscosity. The model shows that if factor A (polymer concentration) is increased by 1 (coded) unit, then $\mu_{100\ \mathrm{cm}}$ is increased by 0.023 units. The polymer concentration had opposite effect as compared to sludge flow rate as it was observed on the yield stress.

Figure 5.8 shows a perturbation plot highlighting the effect of polymer concentration and sludge flow rate on the sludge viscosity at 100 cm from start of the belt filter press. The perturbation plot permits to compare the effect of all the factors at a certain point in the design space. This type of plot is a one factor at a time experimentation and therefore does not show the effect of interactions.

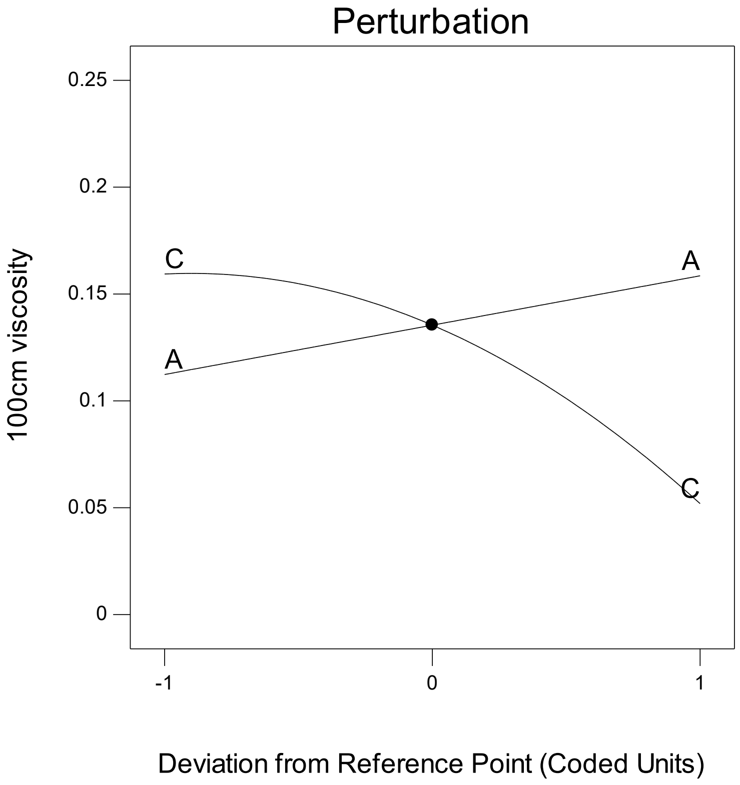


Figure 5.8 Perturbation plot showing the effect of polymer concentration and sludge flow rate on the yield stress

The significant interaction (between the polymer concentration and the sludge flow rate) affecting the sludge viscosity is shown in Figure 5.9. Three dimensional surface plot and 2-D contour plot were constructed and are presented in Figure 5.10, and highlight the positive influence of increasing both the polymer concentration and the sludge flow rate. This figure shows that the sludge viscosity increases directly, with an increase in polymer concentration, while decreases with an increase in the sludge flow rate. At low polymer concentration (0.2%) and high sludge flow rate (20m^3/hr) the sludge viscosity was at the lowest about 0 Pa.s. There was a significant increase in the sludge viscosity to about 0.1 Pa.s at high polymer concentration (0.3%) and high sludge flow rate. It was observed at both low polymer concentration and low sludge flow rate the sludge viscosity was much higher compared to high polymer concentration and high sludge flow rate. Similar behaviour was also observed in the case of yield stress.

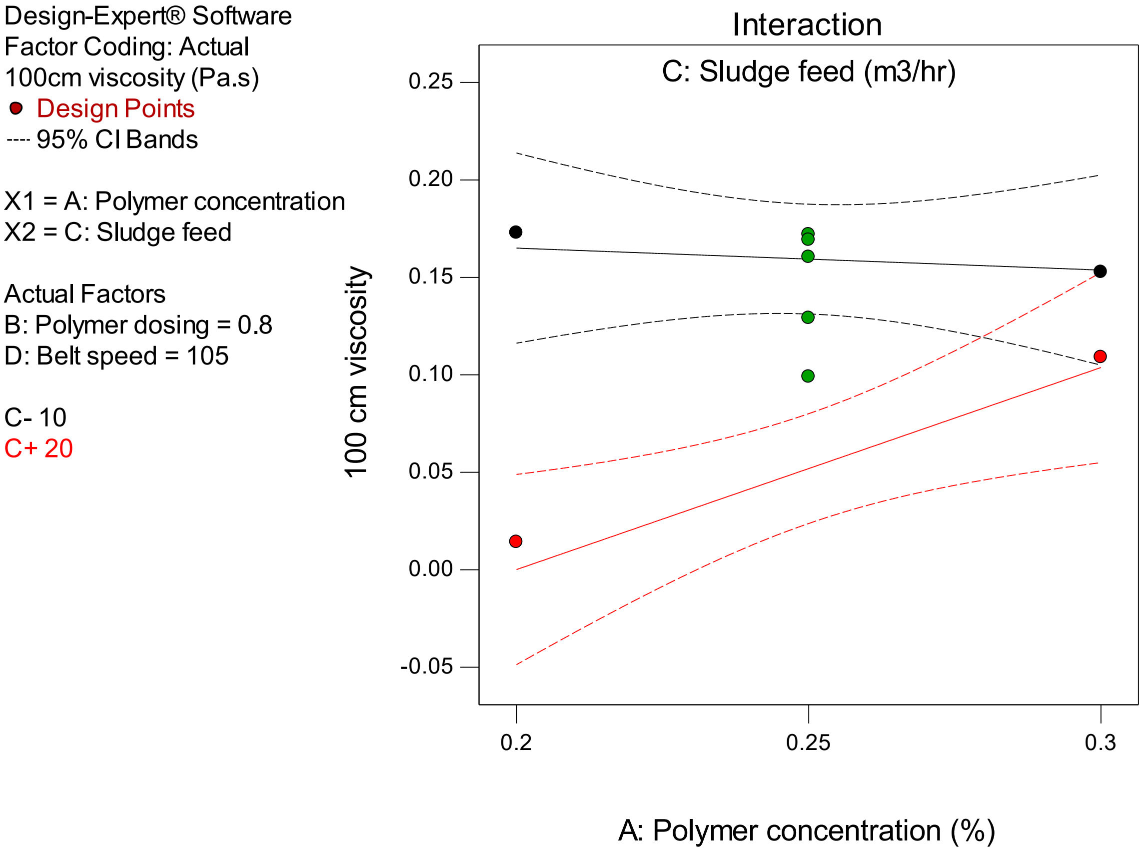


Figure 5.9 Interaction plot showing the most significant interaction effect of polymer concentration and sludge flow rate on the viscosity

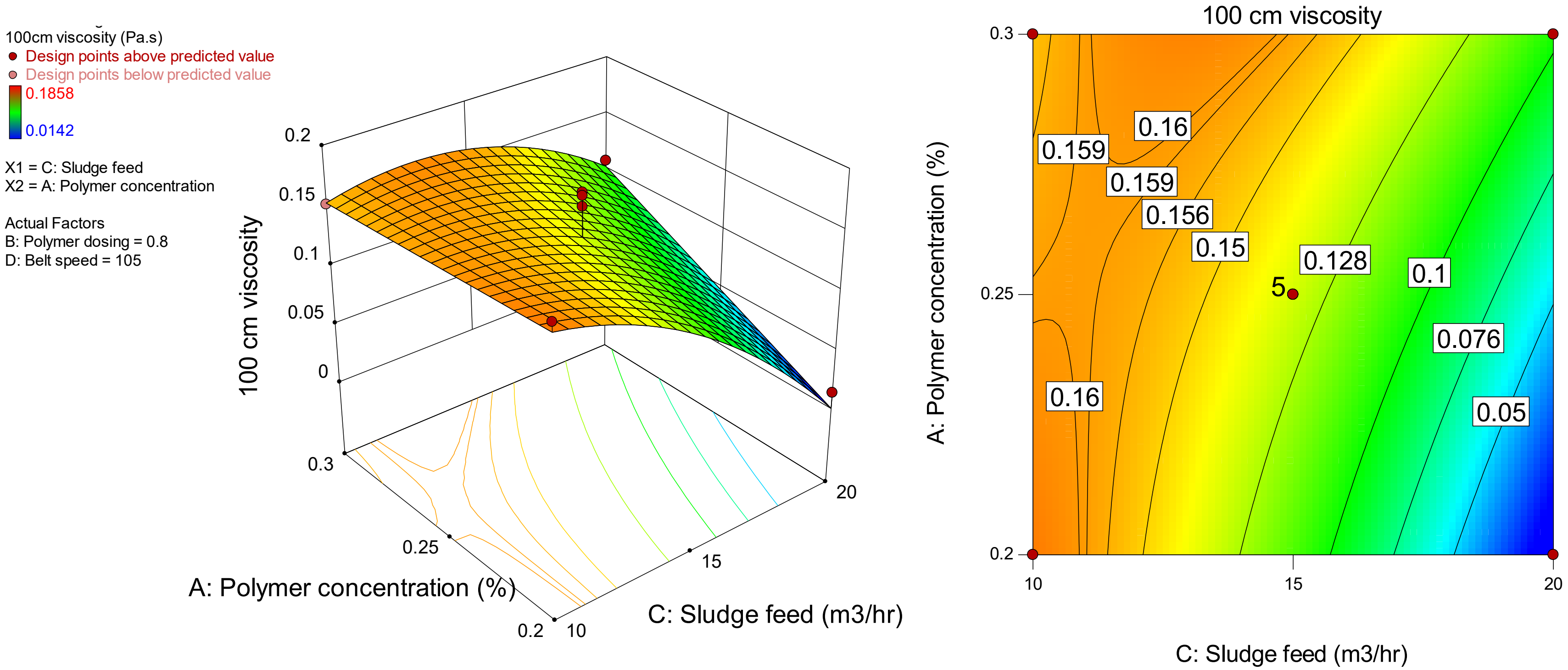


Figure 5.10 3D surface and 2D contour plots showing the viscosity as a function of polymer concentration and sludge flow rate

5.3 Effect of process parameters on the sludge cake solids concentration

Sludge cake solids are one of the performance measures for the belt filter press. Only a few studies have been published on the impact of operating parameters on the cake solids of the dewatered sludge (Olivier & Vaxelaire, 2005). The obtained BBD experimental data was then analysed by building regression models by means of least squares fitting. The sequential model sum of squares and model summary statistics in order to acquire effective regression models among various models, for example, linear, interactive, and quadratic, are shown in Table 5.4. These sums of squares were computed after the fit and were used to test the effects for making significant contributions to the model or not. From Table 5.4, it can be seen that p-values for all the models are above 0.05 except that of the mean model. This indicates that these models are not significant, therefore, they are not appropriate to fit this data. This leaves us with a mean model to fit this data. A model deemed to be significant when its p-value is less than 0.05 at a 95% significance level. The mean model, which uses the mean for every predicted value, generally would be used if there are no informative predictor variables. The mean model was therefore selected to fit the experimental data for sludge cake solids concentration.

Table 5.4 ANOVA statistical summary for each model for sludge cake solids

	Sequential	*Lack of Fit*	*R^2*	*Adjusted R^2*	*Predicted R^2*
Source	**p-value**	**p-value**			
Mean	< 0.0001	–	–	–	–
Linear	0.7229	0.3578	0.0795	-0.0739	-0.3897
2FI	0.6289	0.3131	0.2604	-0.1504	-1.2156
Quadratic	0.9611	0.2154	0.2903	-0.4194	-2.6513

Based on the obtained mean model, the relationship between the sludge cake solids and the process parameters is described by Equation 5.5 which is a constant.

$$\text{sludge cake solids} = 137.95 \qquad \text{Equation 5.5}$$

The validation of the model is important to check the adequacy of the model. In this case, it was not necessary to check the adequacy of the model, as the model uses only the average value (constant) to predict the cake solids. This model indicates that regardless of the changes done on the process parameters the belt press will produce a sludge cake of about 137.95 g/l or 13.7% solids. These results were similar to those found by Johnson and co-workers (1992), who evaluated the influence of individual belt press operating parameters (sludge flow rate, polymer dosing, belt speed and others) on the sludge cake solids. They could not establish any correlations between these operating parameters. Ormeci (2007) found that a full-scale treatment plant was dosing polymer at 10% polymer – to – sludge ratio (10 g/kg dry solids) before dewatering and producing a cake solids of about 18%. However, when the polymer dose was decreased to 5% (5 g/kg dry solids) the cake solids remained at about 18%. The treatment plant was using a rotary press for dewatering compared to a belt filter press in this study. Also, the results of this study are conflicting that of Olivier and Vaxelaire (2005) who found cake solids increased by decreasing the belt speed from 1.5 m/min to 0.1 m/min. The belt speed in this study varied between 3.36 m/min to 4.44 m/min which is not in the same range used by Olivier and Vaxelaire. Therefore, cake solids concentration cannot be used alone to determine the measure of performance for dewatering process, as it may lead to incorrect conclusions.

5.4 Effect of process parameters on the filtrate solids

5.4.1 Development of filtrate suspended solids model

When the experiments were conducted for each run, the filtrate solids were measured in the filtrate stream of the belt filter press. As a result of analysing the measured responses using the Design-Expert software, the significance test for the regression models and the significance test of individual model coefficients were determined by the same statistical software package for all responses. A stepwise selection procedure (stepwise backwards) was used to reject terms that do not make a significant contribution to the model. The quadratic model was found to be significant having the p-value of less than 0.0001 as shown in Table 5.5. Also in this table the significant model terms with p-value of less than 0.05 are shown, in this case are polymer concentration (A), polymer dosing (B), Sludge flow rate (C), the interactions between polymer concentration and sludge flow rate, (AC), and between polymer dosing and sludge flow rate, (BC), lastly the quadratic effects of polymer concentration (A^2) and sludge flow rate (C^2). A p-value that is lower than 0.05 suggests that the model is statistically significant at the 5% level of significance. The

R^2 and adjusted R^2 were found to be 0.95 and 0.93 respectively. These high values suggest that this quadratic model fits the data well.

Table 5.5 ANOVA for filtrate solids quadratic model

ANOVA for Response Surface modified quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	19.85	7	2.84	55.94	< 0.0001	significant
A	0.94	1	0.94	18.62	0.0003	
B	0.99	1	0.99	19.47	0.0002	
C	10.68	1	10.68	210.67	< 0.0001	
AC	0.41	1	0.41	8.16	0.0094	
BC	1.76	1	1.76	34.65	< 0.0001	
A^2	0.33	1	0.33	6.47	0.0189	
C^2	5.00	1	5.00	98.58	< 0.0001	
Residual	1.06	21	0.051			
Corrected Total	20.92	28				

R^2 =0.95; adjusted R^2 = 0.93

The quadratic model was found to represent the relationship between the filtrate suspended solids (FSS) and the input variables. The final model terms of coded factors are presented in Equation 5.6 and Equation 5.7 for uncoded (actual) factors. Where B represents the polymer dosing, BC (m^6/hr^2) is the interaction between polymer concentration and sludge flow rate, A^2 is the quadratic effect of polymer concentration.

$$\sqrt{\mathrm{FSS}} = 0.95 - 0.28^*\mathrm{A} - 0.29^*\mathrm{B} + 0.94^*\mathrm{C} - 0.32^*\mathrm{AC} - 0.66^*\mathrm{BC} + 0.22^*\mathrm{A}^2 + 0.85^*\mathrm{C}^2 \qquad \text{Equation 5.6}$$

$$\sqrt{\mathrm{FSS}} = -5.805 - 29.906^*\mathrm{A} + 17.013^*\mathrm{B} + 0.5495^*\mathrm{C} - 1.286^*\mathrm{AC} - 1.325^*\mathrm{BC} + 87.184^*\mathrm{A}^2 + 0.034^*\mathrm{C}^2 \qquad \text{Equation 5.7}$$

These models can be used to predict the filtrate solids within the range of the factorial trial, by substituting the values of A, B and C or their -1 to 1 codes as shown in Table 3.2.

In Equation 5.6 a positive sign before a term indicates an increasing effect, while a negative sign indicates a decreasing effect on the filtrate solids. The presence of the binary terms in Equation 5.6 indicates that the filtrate solids depends on both single and mixture variables. The binary terms show that there is a decreasing effect from both AC and BC on the filtrate solids.

5.4.2 Adequacy of filtrate solids model

The adequacy of a developed mathematical model for filtrate solids was assessed by constructing predicted versus actual and normal probability plots for the experimental data. Diagnostic plots such as normal probability plot (Figure 5.11) is an appropriate graphical method for checking normality of residuals, when the data lies very close on a straight line, it affirms that the observed data was normal distributed. Furthermore, predicted versus actual (Figure 5.12) is useful for comparing predicted and experimental values. A good agreement between experimental data and the predicted values by the developed model can be seen in Figure 5.12. This was also affirmed by the R^2 value of 0.95, indicating that the model can explain 95% of the variation.

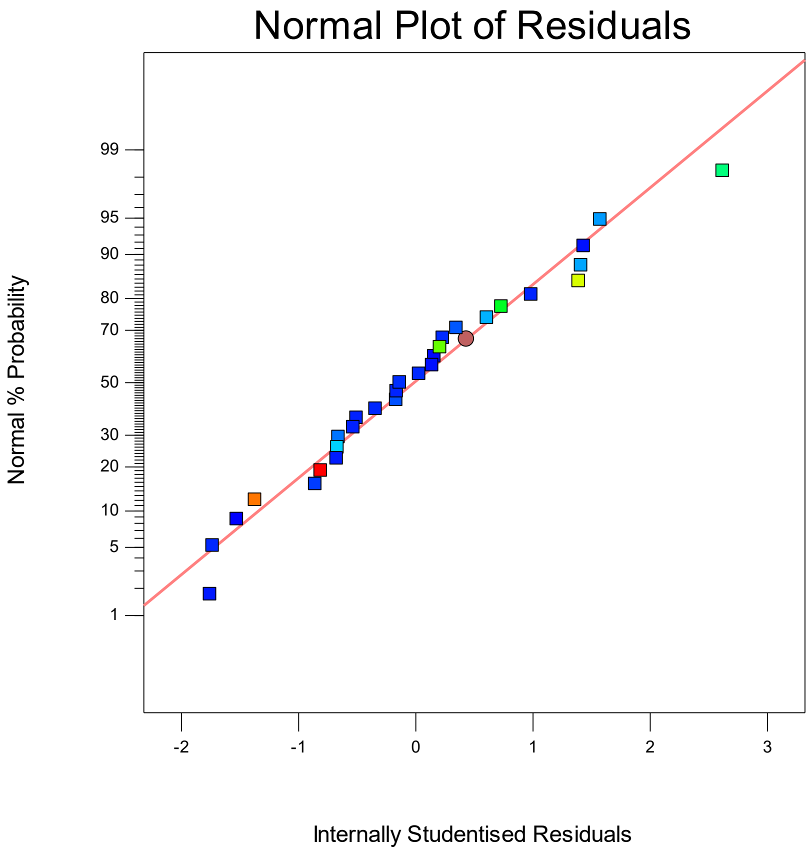


Figure 5.11 Normal plot showing the link between normal probability (%) and internally studentised residuals for filtrate suspended solids

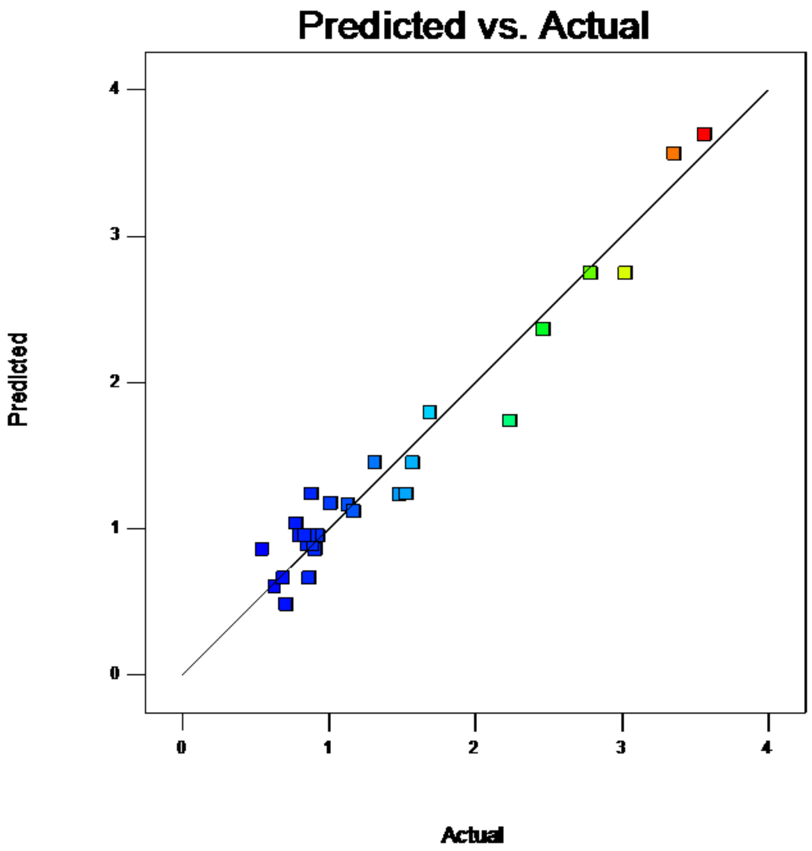


Figure 5.12 Predicted vs actual (experimental) values for filtrate solids

5.4.3 Effect of process parameters on the filtrate solids

The filtrate solids are directly related to the process parameters in this investigation, either as a main or as part of an interaction effect. It has already been shown that the belt press speed does not have a significant effect on the filtrate solids, therefore this factor would not be discussed. The reason for predicting the filtrate solids is to develop a model that can be used by plant operators. This model will aid the plant operators to determine whether the plant is operating within the allowable filtrate solids based on process parameters.

5.4.3.1 Main effect of process parameters on the filtrate solids

The main effects of process parameters (A, B, C) on the filtrate solids have been represented in Figure 5.13 shows a perturbation plot highlighting the effect of polymer concentration, polymer dosing and sludge flow rate on the filtrate solids. The perturbation plot permits to compare the effect of all the factors at a certain point in the design space.

After developing the model for predicting filtrate solids, the primary factor most affecting the filtrate solids appears to be the sludge flow rate (C). The model indicates that if the sludge flow rate changes 1 coded unit, then the filtrate solids would also change by 0.94 units. It is because increasing sludge flow rate increases the solids loaded on the belt filter press. By keeping other factors constant (0 coded unit), the increase in sludge flow rate results in weak flocculation which means that when sludge is pressed the solids pass through the pores of the belt.

It can be seen in Figure 5.13 that both the polymer concentration and polymer dosing have low effect on the filtrate solids. The model shows that if polymer concentration and polymer dosing are increased by 1 (coded) unit, the filtrate solids decreases by 0.28 and 0.29 units respectively. Both the polymer concentration and polymer dosing have an opposite effect as compared to sludge flow rate.

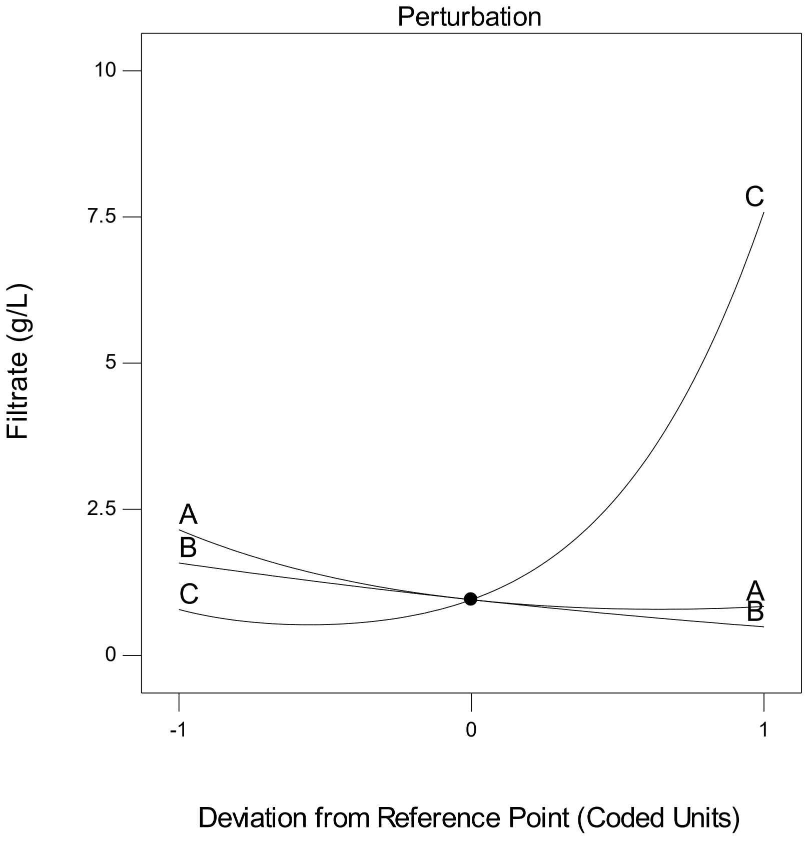


Figure 5.13 Perturbation plot showing the individual effect of polymer concentration and sludge flow rate on the filtrate solids

5.4.3.2 Interaction effect of process parameters on the filtrate solids

Other than the individual effect contributed by each main process parameter, the filtrate solids were also influenced by the interaction variables. The interaction between polymer dosing and the sludge flow rate, parameter BC, was found to be the second most influential factor and the largest interaction affecting the filtrate solids. The model indicates that if this parameter BC, is increased by 1 coded unit, the filtrate solids decreases by 0.66 units. This effect was higher than polymer concentration and polymer dosing.

The interaction between polymer concentration and the sludge flow rate, parameter AC, was found to be the third most influential factor and the second largest interaction affecting the filtrate solids. The model indicates that if this parameter AC, is increased by 1 coded unit, the filtrate solids decreases by 0.32 units. This effect was also higher than polymer concentration and polymer dosing.

Three dimensional surface plots and 2-D contour plots were constructed for polymer concentration and sludge flow rate and also for polymer dosing and sludge flow rate in order to gain a better understanding of the interaction effects of process parameters on the filtrate solids. The effect of sludge flow rate and polymer dosing on the filtrate solids at constant polymer concentration (0.25%) is presented in Figure 5.14. It can be seen that at a high sludge flow rate (20 m^3/hr), there is a pronounced decrease in the filtrate solids as the polymer dosing increases from 0.7 m^3/hr to 0.9 m^3/hr. Although there is a significant decrease in filtrate solids the sludge is still underdosed as the filtrate solids are above the required limit of 1 g/L. At low polymer dosing (0.7 m^3/hr), filtrate solids decrease with the decrease in sludge flow rate. A sludge flow rate below 14 m^3/hr seems to be ideal for keeping filtrate solids below the required limit at low polymer dosing. At a high polymer dosing (0.9 m^3/hr), the filtrate solids decrease with the decrease in sludge flow rate up to about 13 m^3/hr. However, below this sludge flow rate of 13 m^3/hr, the filtrate solids tends to increase which indicates an overdosing effect.

The effect of sludge flow rate and polymer dosing on the filtrate solids at constant polymer dosing (0.8 m^3/hr) is presented in Figure 5.15. It can be seen that at a high sludge flow rate (20 m^3/hr), there is an apparent decrease in the filtrate solids as the polymer concentration increases from 0.2% to 0.3%. This indicates that operating the plant at high sludge flow rates would not produce the required filtrate irrespective of the polymer concentration. Although operating the plant at low sludge flow rates at any polymer concentration produces filtrate solids that are within the required limits, the cost of operating at 0.2% and 0.3% polymer concentration would differ.

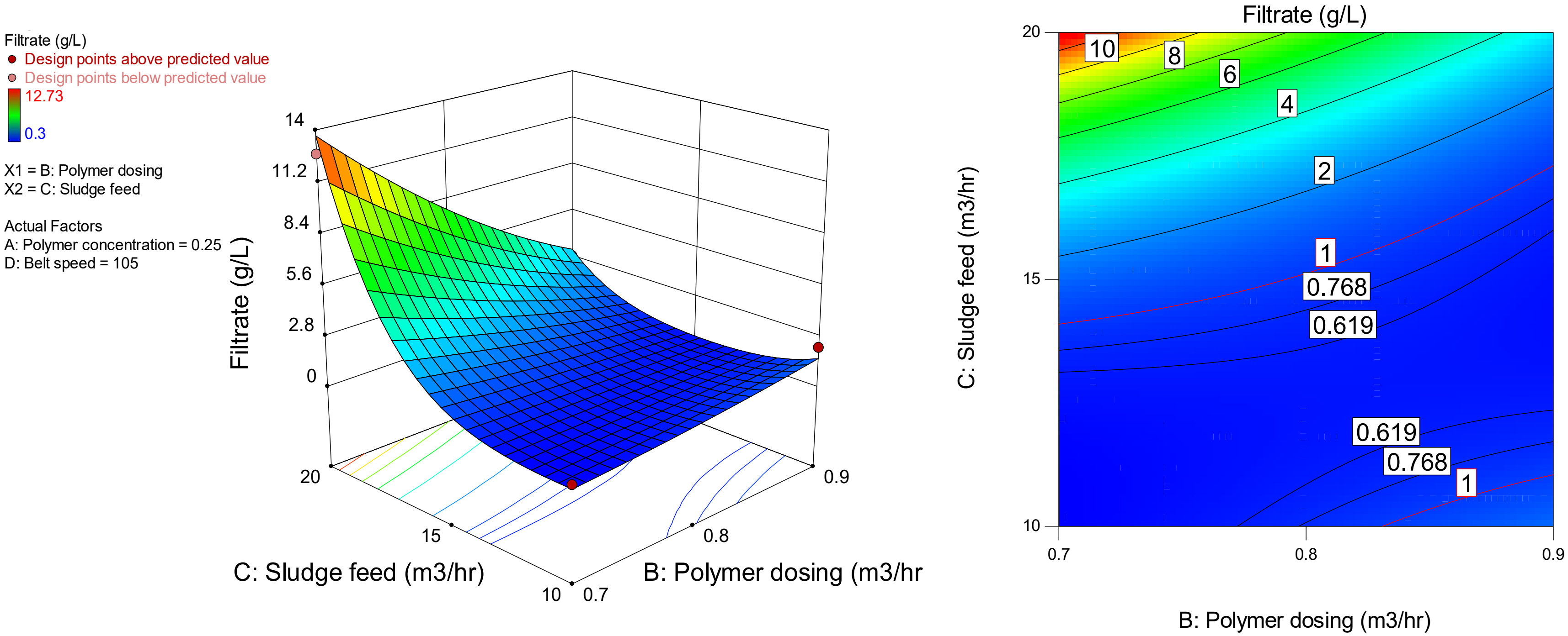


Figure 5.14 3D surface and 2D contour plots showing the effect of polymer dosing and sludge flow rate on the filtrate solids

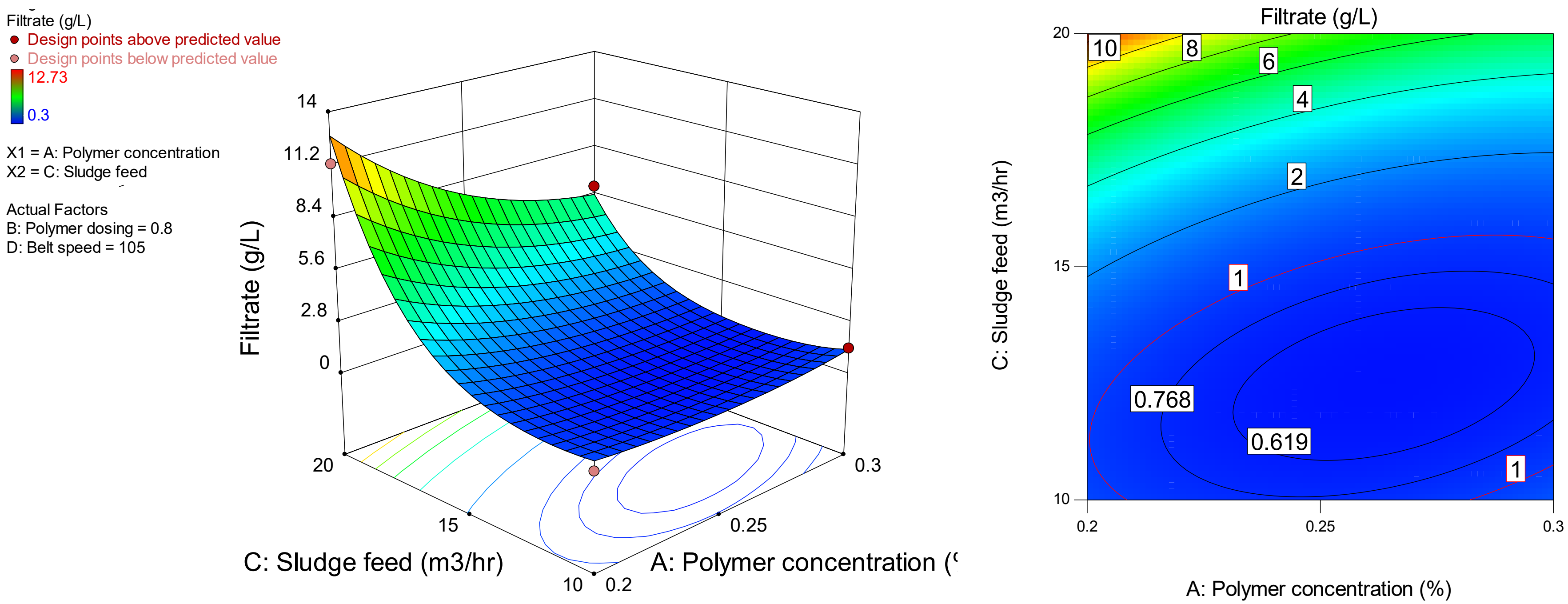


Figure 5.15 3D surface and 2D contour plots showing the effect of polymer concentration and sludge flow rate on the filtrate solids

5.5 Effect of process parameters on the solids capture

5.5.1 Development of solids capture model

When the experiments were conducted for each run, the solids capture was calculated using Equation 5.8 (Turovskiy & Mathai, 2006). As a result of analysing the measured responses using the Design-Expert software, the significance test for the regression models and the significance test of individual model coefficients were determined by the same statistical software package for all responses. A stepwise selection procedure (stepwise backwards) was used to reject terms that do not make a significant contribution to the model. The quadratic model was found to be significant having a p-value of less than 0.0001 as shown in Table 5.6. Also in this table the significant model terms with p-value of less than 0.05 are shown. Polymer concentration (A), polymer dosing (B), sludge flow rate (C), the interactions between polymer concentration and polymer dosing (AB), polymer concentration and sludge flow rate, (AC), and between polymer dosing and sludge flow rate, (BC), lastly the quadratic effects of polymer concentration (A^2) and sludge flow rate (C^2). A p-value that is lower than 0.05 suggests that the model is statistically significant at the 5% level of significance. The R^2 and adjusted R^2 were found to be 0.96 and 0.94 respectively. These high values suggest that this quadratic model fits the data well.

$$\text{Solids capture (\%)} = \frac{\text{solids in feed} - \text{solids in filtrate}}{\text{solids in feed}} \text{x} 100 \qquad \text{Equation 5.8}$$

Table 5.6 ANOVA for solids capture quadratic model

ANOVA for Response Surface modified quadratic model

Source	Sum of Squares	df	Mean Square	F Value	p-value	
Model	3574.05	8	446.76	64.66	< 0.0001	significant
A	161.96	1	161.96	23.44	< 0.0001	
B	173.45	1	173.45	25.10	< 0.0001	
C	1785.33	1	1785.33	258.38	< 0.0001	
AB	35.13	1	35.13	5.08	0.0355	
AC	120.54	1	120.54	17.44	0.0005	
BC	328.90	1	328.90	47.60	< 0.0001	
A^2	70.05	1	70.05	10.14	0.0047	
C^2	951.31	1	951.31	137.68	< 0.0001	
Residual	138.19	20	6.91			
Corrected Total	3712.24	28				

$R^2 = 0.96$; adjusted $R^2 = 0.94$

The quadratic model was found to represent the relationship between the solids capture (SC) and the input variables. The final model terms of coded factors are presented in Equation 5.9 and Equation 5.10 for uncoded (actual) factors.

$$SC = 97.10 + 3.67^*A + 3.80^*B - 12.20^*C - 2.96^*AB + 5.49^*AC + 9.07^*BC - 3.19^*A^2 - 11.74^*C^2 \qquad \text{Equation 5.9}$$

$$SC = 81.03 + 855.42^*A - 85.85^*B - 8.35^*C - 592.68^*AB + 21.96^*AC + 18.14^*BC - 1274.35^*A^2 - 0.47^*C^2 \qquad \text{Equation 5.10}$$

These models can be used to predict the solids capture within the range of the factorial trial, by substituting the values of A, B and C or their -1 to 1 codes as shown in Table 3.2.

In Equation 5.9 a positive sign before a term indicates an increasing effect, while a negative sign indicates a decreasing effect on the solids capture. The presence of the binary terms in Equation

5.9 indicates that the solids capture depends on both single and mixture variables. The binary terms show that there is an increasing effect from both AC and BC on the solids capture while AB has a decreasing effect.

5.5.2 Adequacy of solids capture model

The adequacy of a developed mathematical model for solids capture was assessed by constructing predicted versus actual and normal probability plots for the experimental data. The normal probability plot shown in Figure 5.16 illustrates that the viscosity residuals were normally distributed. A good agreement between experimental data and the predicted values by the developed model can be seen in Figure 5.17. This was also affirmed by the R^2 value of 0.96, indicating that the model can explain 96% of the variation.

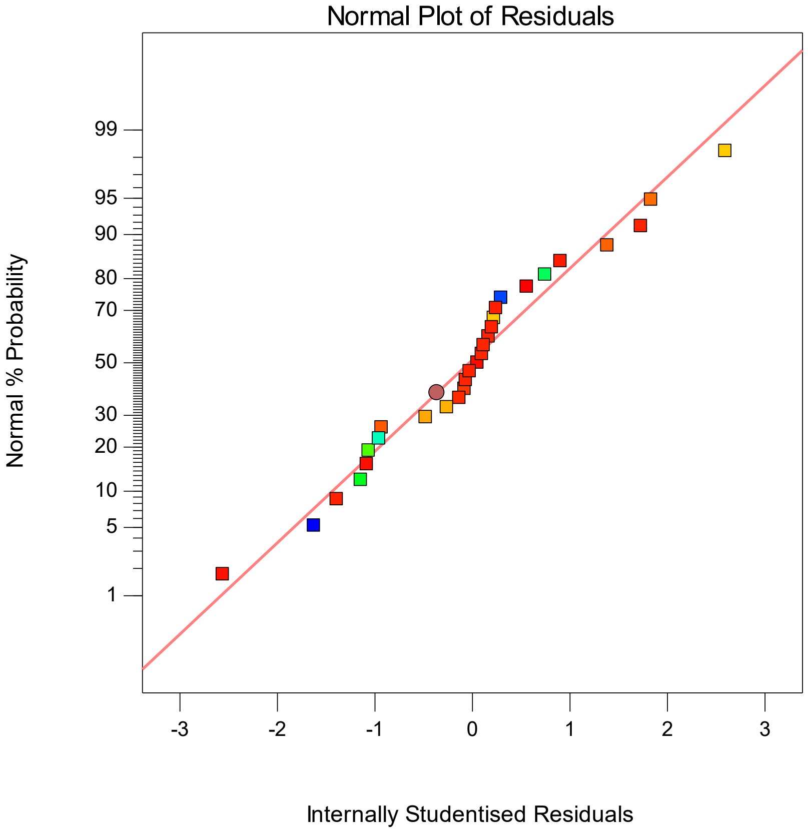


Figure 5.16 Normal plot showing the link between normal probability (%) and internally studentised residuals for solids capture

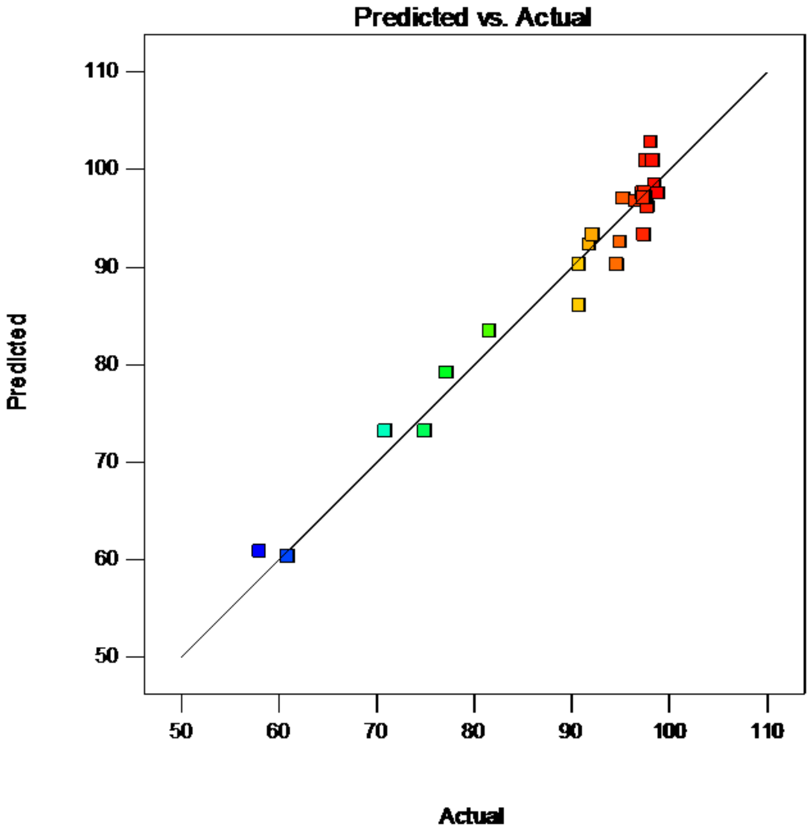


Figure 5.17 Predicted vs actual (experimental) values for solids capture

5.5.3 Effect of process parameters on the solids capture

The solids capture are directly related to the process parameters in this investigation, either as a main or as part of an interaction effect. It has already been shown that the belt press speed does not have a significant effect on the solids capture, therefore this factor would not be discussed.

5.5.3.1 Main effect of process parameters on the solids capture

The main effects of process parameters (A, B, C) on the solids capture have been represented in Figure 5.18. This shows a perturbation plot highlighting the effect of polymer concentration, polymer dosing and sludge flow rate on the solids capture. The perturbation plot permits to compare the effect of all the factors at a certain point in the design space.

After developing the model for predicting solids capture, the primary factor most affecting the solids capture appears to be the sludge flow rate (C). The model indicates that if the sludge flow rate 1 coded unit, then solids capture decreases by 12.2 units. It is because increasing the sludge flow rate increases the amount of solids loaded on the belt filter press thus reduces the efficiency of the BFP. By keeping other factors constant (0 coded unit), the increase in sludge flow rate results in weak flocculation which means that when sludge is pressed the solids pass through the pores of the belt resulting in fewer solids being captured.

It can be seen in Figure 5.18 that both the polymer concentration and polymer dosing have a low effect on the solids capture compared to sludge flow rate. The model shows that if polymer concentration or polymer dosing is increased by 1 (coded) unit, the solids capture increases by 3.67 or 3.80 units respectively. Both the polymer concentration and polymer doing have an opposite effect as compared to sludge flow rate.

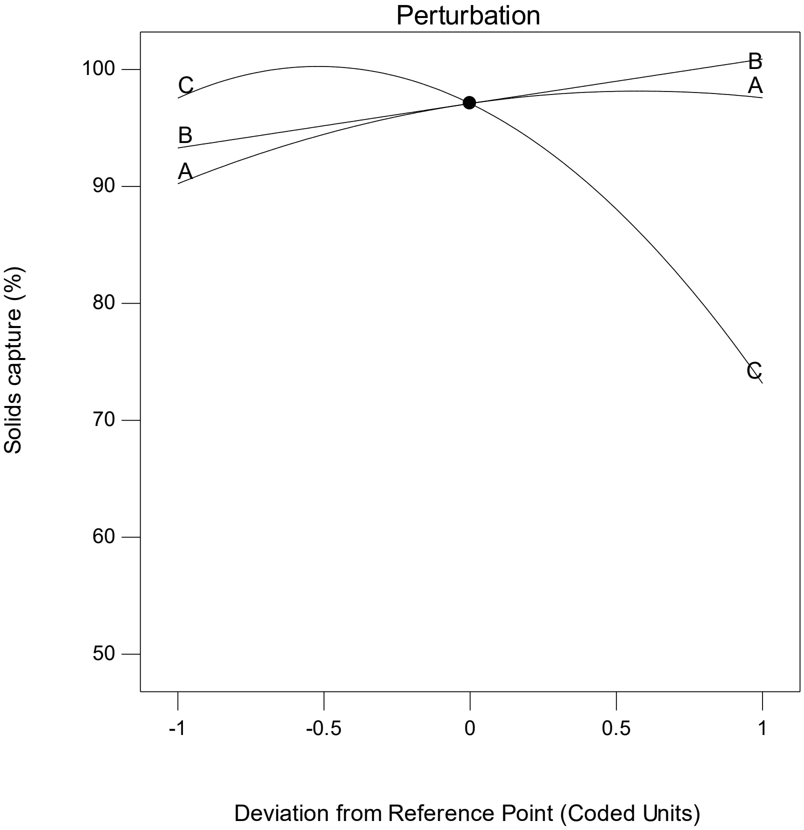


Figure 5.18 Perturbation plot showing the individual effect of polymer concentration, polymer dosing and sludge flow rate on the solids capture

5.5.3.2 Interaction effect of process parameters on the solids capture

In addition to the individual effect contributed by each main process parameter, the solids capture was also influenced by the interaction variables. The interaction between polymer dosing and the sludge flow rate, parameter BC, was found to be the second most influential factor and the largest interaction affecting the solids capture. The model indicates that if this parameter BC, is increased by 1 coded unit, the solids capture increases by 9.07 units. This effect was higher than polymer concentration and polymer dosing.

The interaction between polymer concentration and the sludge flow rate, parameter AC, was found to be the third most influential factor and the second largest interaction affecting the solids capture. The model indicates that if this parameter AC, is increased by 1 coded unit, the solids capture increases by 5.49 units. This effect was also higher than polymer concentration and polymer dosing.

The interaction between polymer concentration and the polymer dosing, parameter AB, was found to be the third largest interaction affecting the solids capture. The model indicates that if this parameter AB, is increased by 1 coded unit, the solids capture decreases by 2.96 units. Although this effect was lower than polymer concentration and polymer dosing, it remains important.

Three dimensional surface plots and 2-D contour plots (Figure 5.19 to Figure 5.21) were constructed for polymer concentration and sludge flow rate and also for polymer dosing and sludge flow rate in order to gain a better understanding of the interaction effects of process parameters on the solids capture.

The effect of polymer concentration and polymer doing on the solids capture at constant sludge flow rate (15 m^3/hr) is presented in Figure 5.19. It can be seen that although the solids capture is very high at higher polymer concentration (0.3%), for an increase in polymer dosing from 0.7 m^3/hr to 0.9 m^3/hr, there is only a slight increase in solids capture from 96.6% to 99.3%. Similarly, at low polymer concentration (0.2%), the increase in polymer dosing results in a solids capture increase from 84.1% to 96.1%. Although at a high polymer dosing (0.9 m^3/hr), an increase in polymer concentration resulted in no significant increase nor decrease in solids capture but at low polymer dosing (0.7 m^3/hr) the solids capture increased from 84.1% to 96%.

The effect of sludge flow rate and polymer concentration on the solids capture at constant polymer dosing (0.8 m^3/hr) is presented in Figure 5.20. It can be seen that at a high sludge flow rate (20 m^3/hr), as the polymer concentration increases from 0.2% to 0.3%, the solids capture also increases from 65% to 81%. Again as already been seen in the case of the filtrate, this indicates that operating the Plant Jt a high sludge flow rate would not produce the required solids capture irrespective of the polymer concentration. Although operating the Plant Jt low sludge flow rate at any polymer concentration produces similar solids capture that is 96%, the cost of operating at 0.2% and 0.3% polymer concentration would differ significantly.

The effect of sludge flow rate and polymer dosing on the solids capture at constant polymer concentration (0.25%) is presented in Figure 5.21. It can be seen that at a high sludge flow rate (20 m^3/hr), there is a significant increase in the solids capture from 61% to 85% as the polymer dosing increases from 0.7 m^3/hr to 0.9 m^3/hr. Although there is a significant increase in solids capture but the sludge is still underdosed as the solids capture is low (less than 90%). At low polymer dosing (0.7 m^3/hr), solids capture increases with the decrease in sludge flow rate. A sludge flow rate below 14 m^3/hr seems to be ideal for keeping solids capture below the required limit at low polymer dosing. Also at high polymer dosing (0.9 m^3/hr), the solids capture increases with the decrease in sludge flow rate up to about 13 m^3/hr. However, below this sludge flow rate of 13 m^3/hr, the solids capture tends to decrease which indicates an overdosing effect.

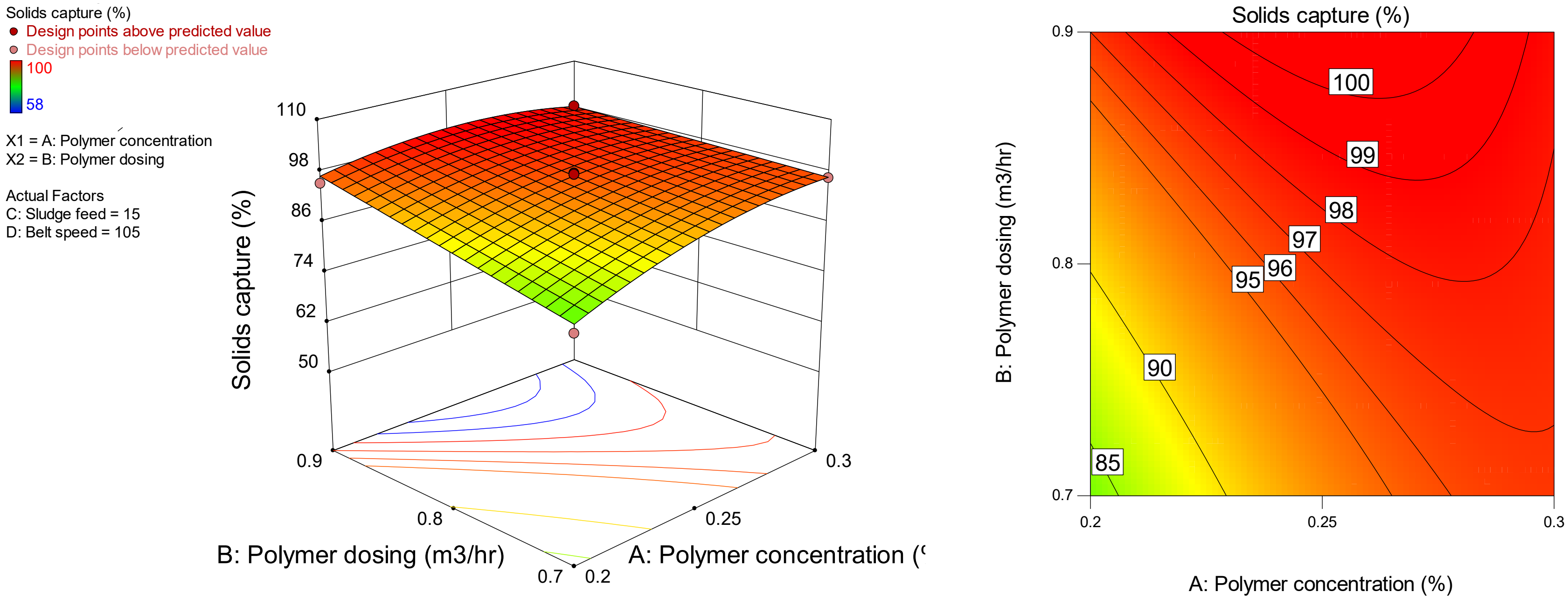


Figure 5.19 3D surface and 2D contour plots showing the effect of polymer dosing and polymer concentration on the solids capture

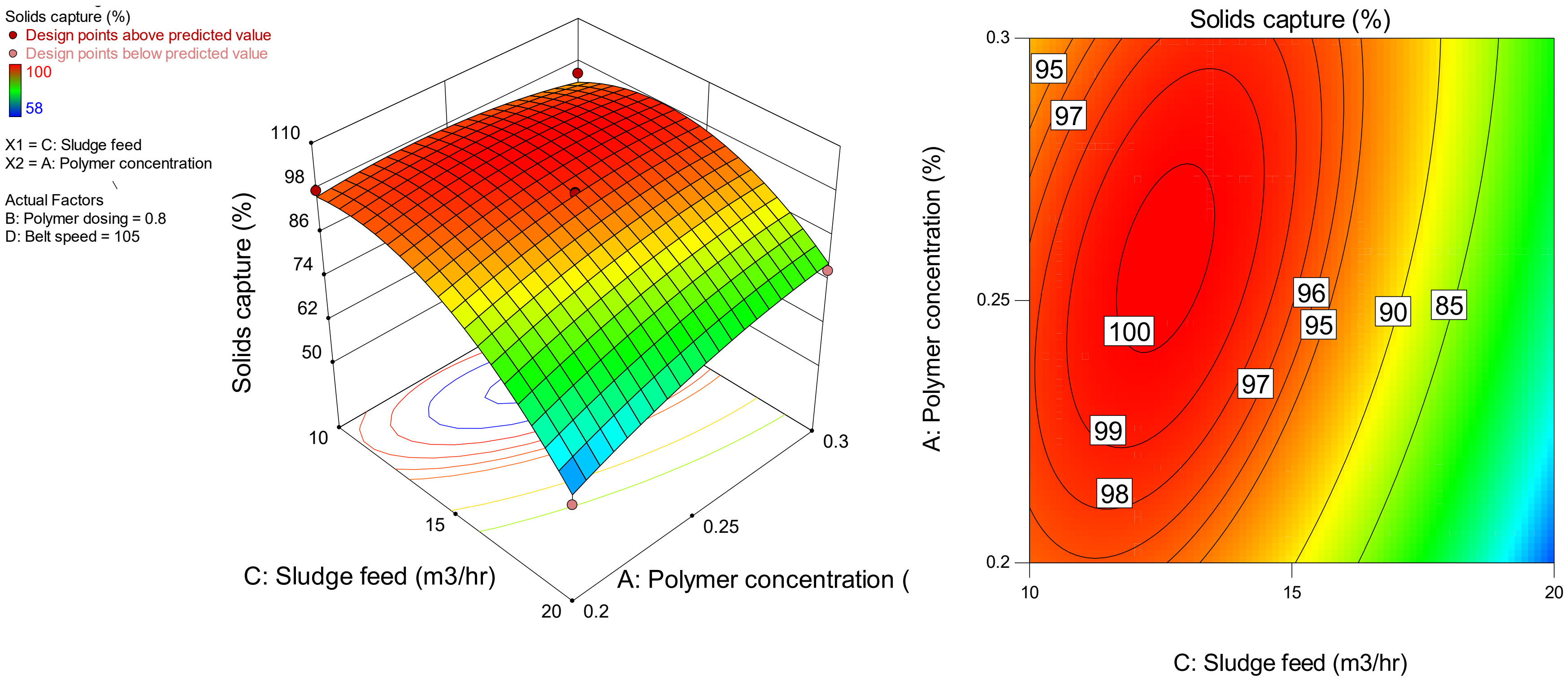


Figure 5.20 3D surface and 2D contour plots showing the effect of polymer concentration and sludge flow rate on the solids capture

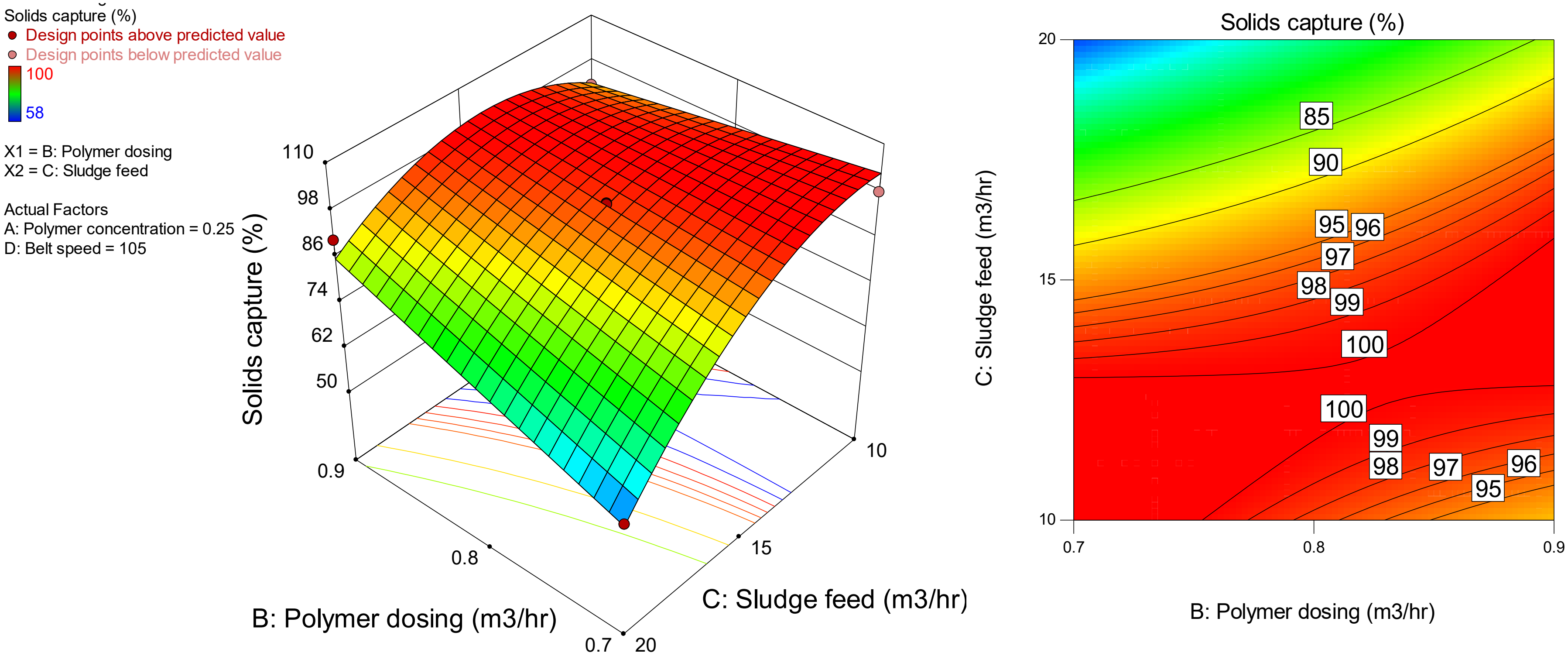


Figure 5.21 3D surface and 2D contour plots showing the effect of polymer dosing and sludge flow rate on the solids capture

5.6 Relationship between sludge rheological properties and cake solids concentration

This analysis was done to evaluate the relationship of both yield stress and a viscosity at 100 cm from the start of the belt filter press with cake solids. This was an effort to link the yield stress or viscosity with cake solids. The relationship between yield stress at 100 cm and cake solids is shown in Figure 5.22(a) and the relationship between viscosity at 100 cm and cake solids in Figure 5.22(b).

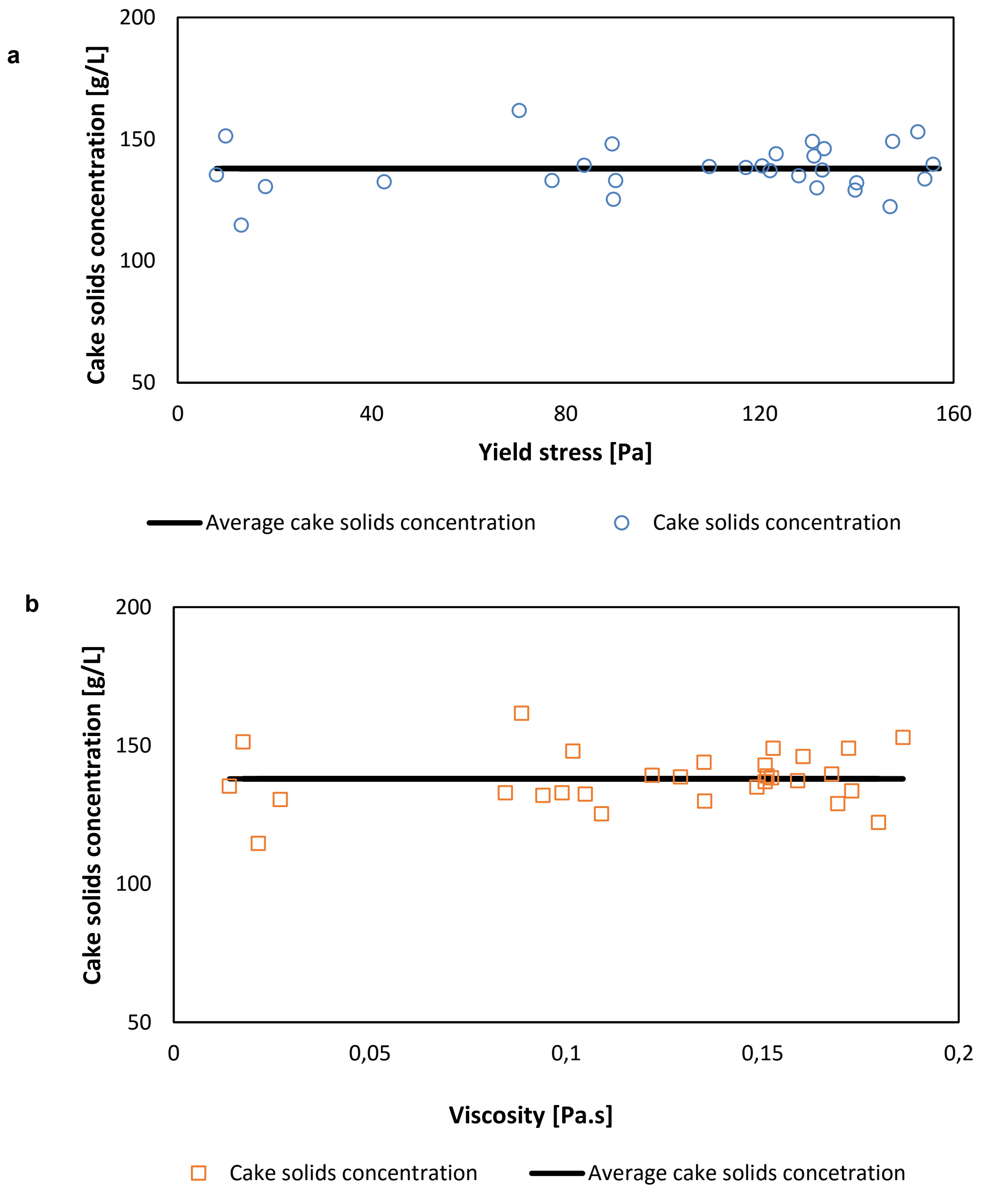


Figure 5.22 (a) Relationship between yield stress at 100 cm and cake solids (b) relationship between viscosity at 100 cm and cake solids

It can be seen that the increase of both the yield stress and the viscosity had little effect on the cake solids. This indicates that cake solids was independent of both the yield stress and the viscosity at 100 cm from the start of the belt filter press with an average value of 138 g/L. Therefore, measuring yield stress or viscosity of the sludge at this point on the belt filter press in trying to optimise the cake solids would not be effective and also the belt filter press performance should not be based on cake solids alone.

5.7 Relationship between sludge rheological properties on the belt and filtrate suspended solids

This analysis was performed to assess the relationship of both yield stress and a viscosity at 100 cm from the start of the belt filter press with FSS. The relationship between yield stress at 100 cm and FSS is shown in Figure 5.23(a) and the relationship between viscosity at 100 cm and FSS in Figure 5.23(b).

It can be seen from Figure 5.23 that the FSS decreases with the increase in yield stress or viscosity. There is an initial sharp decrease in the FSS from 12.73 g/L to 0.65 g/L as the yield stress increased from 10 Pa to 90 Pa, while the viscosity increased from 0.0142 Pa.s to 0.0941 Pa.s. This is a result of the increase of polymer concentration and/or polymer dosing, producing larger and stronger flocs which in turn increases both the yield stress and viscosity.

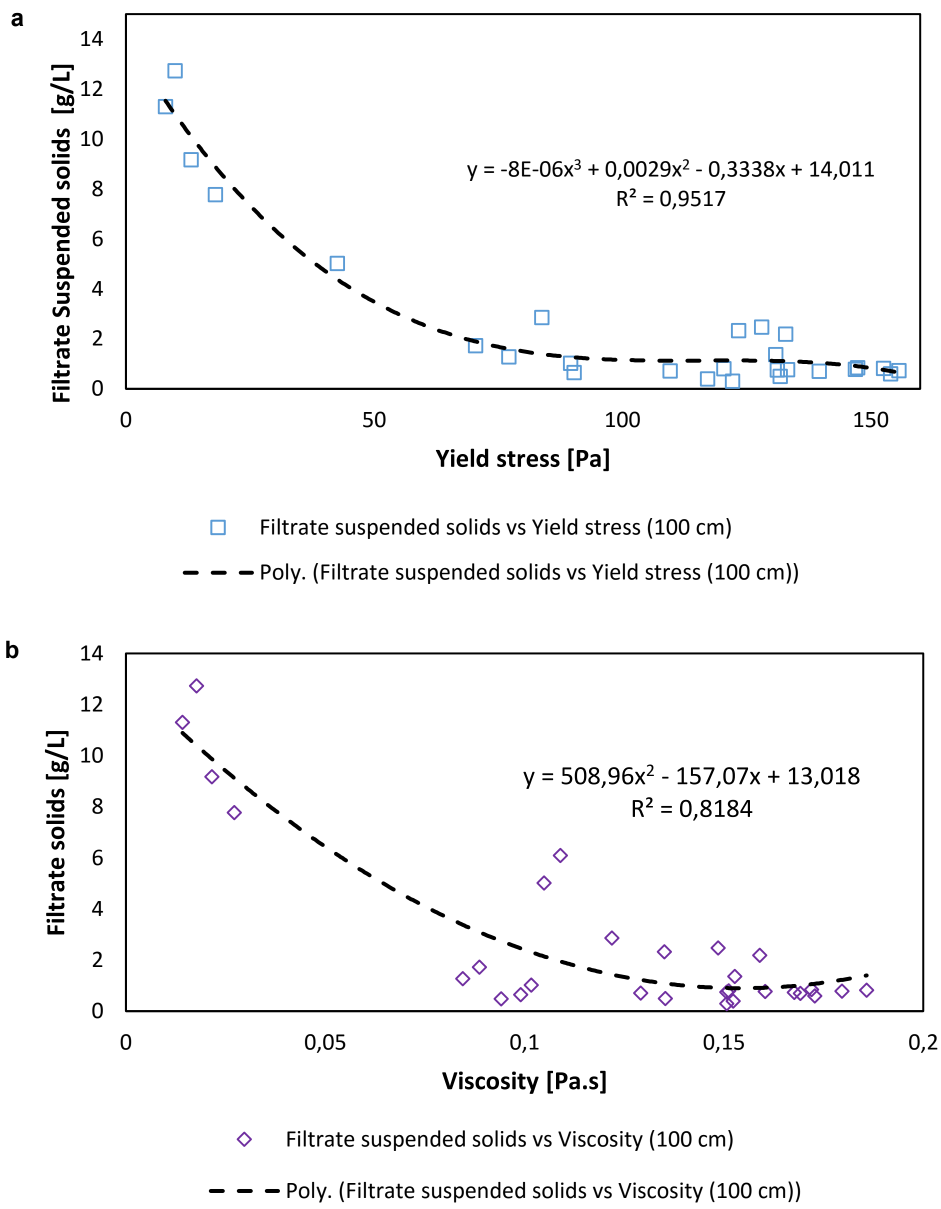


Figure 5.23(a) Relationship between yield stress at 100 cm and FSS (b) relationship between viscosity at 100 cm and FSS

Beyond this point, a further increase in yield stress or viscosity did not decrease or increase the FSS, the polynomial line (black) clearly shows the plateau over the region of 90 Pa to 160 Pa yield stress or 0.1 Pa.s to 0.19 Pa.s viscosity.

The relationship between the yield stress and FSS is well described by Equation 5.11 having the coefficient of determination (R^2) of 0.95. Whereas a relationship between the viscosity and FSS was described by Equation 5.12 having the R^2 of 0.82.

$$\mathrm{FSS} = -8\mathrm{x}10^{-6}\tau_0{}^3 + 0.0029\tau_0{}^2 - 0.3338\tau_0 + 14.01 \qquad \text{Equation 5.11}$$

$$\mathrm{FSS} = 508.96\mu^2 - 157.07\mu + 13.02 \qquad \text{Equation 5.12}$$

One of the important considerations for a WWTP is to produce a filtrate with little suspended solids without having to over condition the sludge. The optimum yield stress and viscosity were found to be approximately 90 Pa and 0.0941 Pa.s respectively. The optimum yield stress and viscosity values correspond to experimental conditions shown in Table 5.7.

Table 5.7 Optimum belt filter press operational parameters

Run	*Polymer concentration %*	*Polymer dosing m³/hr*	*Sludge feed m³/hr*	*Belt speed %*	*Cake solids g/L*	*Solids capture g/L*	*Yield stress Pa*	*Viscosity Pa.s*
21	0.25	0.8	15	105	133	0.65	90	0.0941

5.8 Relationship between rheological properties on the belt and solids capture

This analysis was performed to evaluate the relationship of both yield stress and a viscosity at 100 cm from the start of the belt filter press with solids capture also known as solids recovery. The relationship between yield stress at 100 cm and solids capture from results is shown in Figure 5.24(a), while the relationship between viscosity at 100 cm and solids capture from results shown in Figure 5.24(b).

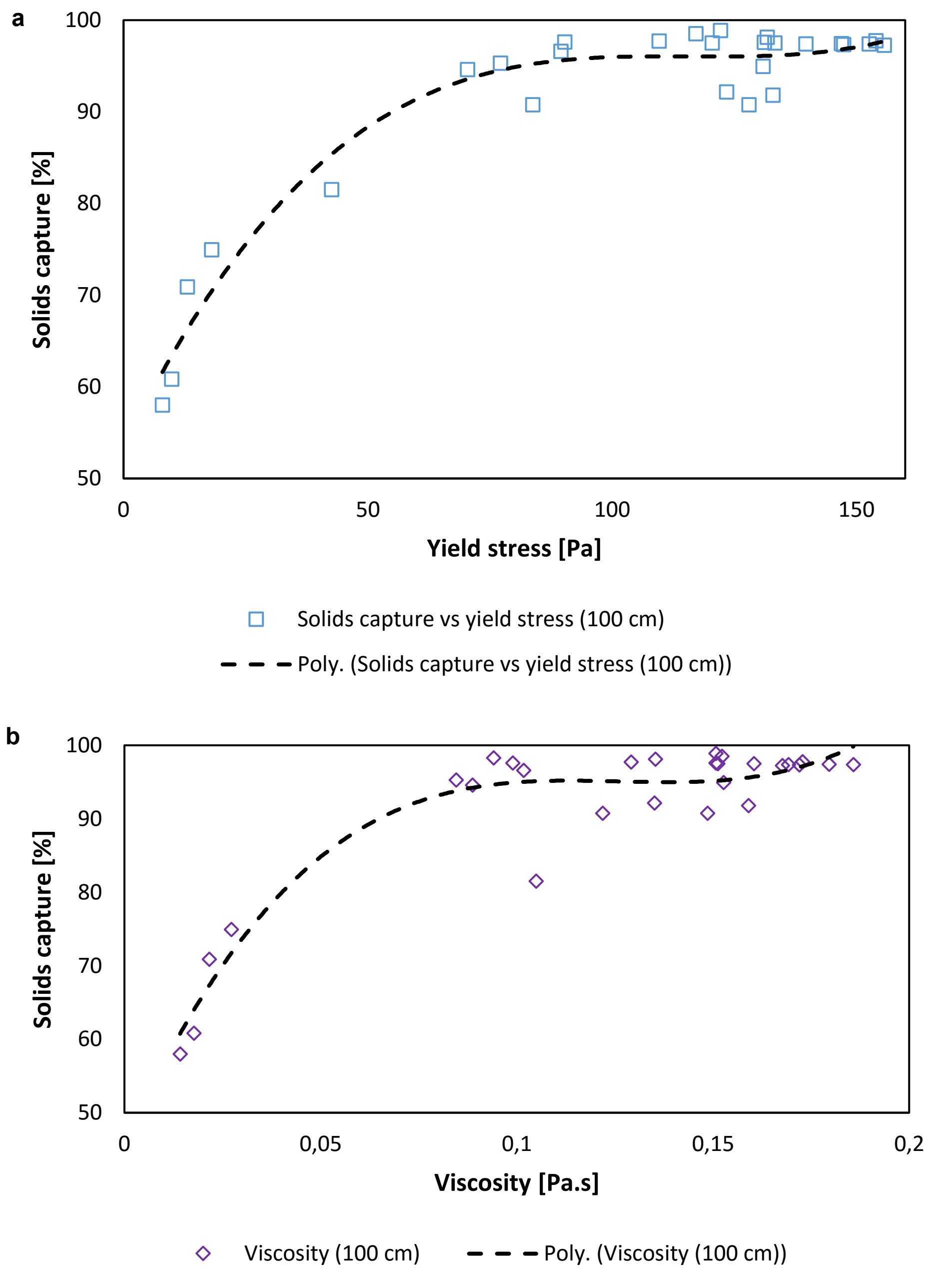


Figure 5.24(a) Relationship between filtrate suspended solids vs yield stress at 100 cm (b) relationship between filtrate suspended solids vs viscosity at 100 cm

It can be seen from Figure 5.24 that there was a considerable increase in solids capture from 58% to 98.3% with an increase yield stress from 8 Pa to 90 Pa and viscosity from 0.014 Pa.s to 0.1 Pa.s. Above this point, a further increase in rheological properties did not result in decrease or increase in the solids captured. The relationship between the yield stress and solids capture is described by Equation 5.13 and for viscosity by Equation 5.14.

$$\text{Solids capture} = 3\text{x}10^{-5}\tau_0{}^3 - 0.0096\tau_0{}^2 + 1.112\tau_0 + 53.35 \qquad \text{Equation 5.13}$$

$$\text{Solids capture} = 25625\mu^3 - 96806\mu^2 + 1206.4\mu + 45.5 \qquad \text{Equation 5.14}$$

Both polymer concentration and dosing increases the yield stress. The effect was similar to the result reported by Pan *et al*. (2001) in that the initial yield stress for sludge increases as the polymer increases, resulting from the increased volume and strength of the flocs. Pan *et al*. (2001), state that the polymer dosage resulting in maximum yield stress is the optimum dosage as it produces flocs that are the hardest to distort. However, in this study that was not observed. The optimum yield stress and viscosity were found to be around 90 Pa and 0.0941 Pa.s respectively and the corresponding experimental conditions are shown in Table 5.8.

Table 5.8 Optimum belt filter press operational parameters

Run	***Polymer concentration %***	***Polymer dosing m^3/hr***	***Sludge feed m^3/hr***	***Belt speed %***	***Cake solids g/L***	***Viscosity Pa.s***	***Yield stress Pa***	***Solids capture %***
21	0.25	0.8	15	105	133	0.0941	90	97.6

This expression that can be used to predict yield stress at 100 cm from the start of the belt press based on the operating parameters. The yield stress from this expression can be used to determine the solids capture or solids in the filtrate. This will enable plant operators to see whether the plant is operating efficiently and does not exceed the FSS required limit without having to physically measure solids capture. This relationship between the FSS or solids capture and yield stress could also be used in selecting best performing polymers. For example, a polymer that gives high yield stress, low FSS and/or high solids capture.

5.9 Conclusion

The effects of BFP operating parameters such as polymer concentration, polymer dosing rate sludge flow rate and belt speed, and the interactions between these parameters were evaluated for their resulting effect on rheological parameters, sludge cake solids, filtrate suspended solids and solids capture in this chapter. A Box-Behnken design was utilised to design the experimental matrix. Different forms of quadratic models were developed based on statistical analysis to predict the effect of operating parameters on rheological parameters, filtrate suspended solids and solids capture. However, no model to predict the sludge cake solids was found as it remained constant over the range of parameters tested.

It was found that sludge flow rate was the most influential parameter of all other responses except on sludge cake solids while the belt speed had an insignificant influence on all the responses. Different interactions between the operating parameters were found to be present and had significant influence on all other responses except on sludge cake solids.

The relationship between rheological properties and sludge cake solids, filtrate suspended solids (FSS) and solids capture were also evaluated. It was found that the sludge cake solids was independent of the rheological properties. The filtrate suspended solids decreased with the increase in rheological properties at 100 cm on the BFP until it reached an optimum after which no further changes were noticeable. On the contrary, solids capture increased with the increase in rheological properties until this optimum. The optimal yield stress and viscosity points were found to be at about 90 Pa and 0.0941 Pa.s respectively.

Chapter 6 Conclusions and recommendations

6.1 Introduction

This chapter presents a summary of the findings of the study on the variability of sludge rheological properties as well as the effect of rheological properties on sludge dewatering in a belt filter press. The findings are summarised with their implications and significance. It also entails recommendations for further work.

6.2 Summary of results

6.2.1 Variability of rheological properties at various WWTPS

Four WWTPs were selected for this study. Rheological properties for activated sludge were measured at different sampling points for twelve weeks. In addtion, the belt filter press operating parameters at the various WWTPs were monitored. For rheological characterisation of the sludge samples, a Bingham model was used to determine the rheological parameters. It was found that the operating parameters for all the plants varied significantly during the twelve-week assessment. The sludge rheological properties for all the considered WWTPs were consistent before the polymer is added, however, once the sludge is dosed with polymer these rheological properties varied. The variability of the rheological properties increased once the polymer was added compared to the feed.

Despite the variation in rheological parameters obtained over time for the various BFPs and operations, the parameters collapsed onto a single curve for each measurement position when presented as a function of solids concentration. This was very useful as it allowed for the development of four power-law correlations that describes the evolution of the yield stress and viscosity from the feed to the 300 cm on the belt before entering the pressure zone.

The rheological properties after polymer addition could be related to the product of the process parameters and these relationships were different for the various BFP systems evaluated, indicating that this variation was only dependent on solids concentration as delivered by the belt filter press at specific operating parameters.

6.2.2 Effect of rheological properties on the belt filter press performance

A four factors three level Box-Behnken experimental design was used to statistically analyse the effect of operating parameters and their interactions on the BFP performance using Stat-Ease Design Expert V 10.0.0 version. The selected parameters were polymer concentration (%), polymer dosing rate (m^3/hr), sludge feed rate (m^3/hr) and belt filter press speed (%). The effects of various operating parameters such as sludge flow rate, belt speed, polymer dosing rate and polymer concentration, and the possible interactions between these parameters were also evaluated on the resulting effect on yield stress, viscosity sludge cake solids, filtrate solids and solids capture. It was found that the relationship between belt filter press operating parameters and responses (yield stress, viscosity, filtrate suspended solids and solids capture) was described by a quadratic function. Belt press speed was found to have no effect on the yield stress, viscosity, filtrate suspended solids and solids capture, while sludge flow rate proved to have a large effect. No correlation was found between the operating parameters and sludge cake solids as it remained reasonably constant over the process parameters tested. Four correlations describing the relationship between the responses and the belt filter press operating parameters were developed.

Table 6.1 gives the significant process parameters and interactions affecting rheological properties, filtrate suspended solids and solids capture.

Table 6.1: Significant process parameters and interactions affecting rheological properties, filtrate suspended solids and solids capture

Responses	**A: Polymer concentration** (%)	**B: Polymer dosing** (m^3/hr)	**C: Sludge feed** (m^3/hr)	**D: Belt speed** (%)	**AB**	**AC**	**BC**
Yield stress	✓	-	✓	-	-	✓	-
Viscosity	✓	✓	✓	-	-	✓	-
Sludge cake solids	-	-	-	-	-	-	-
Filtrate suspended solids	✓	✓	✓	-	-	✓	✓
Solids capture	✓	✓	✓	-	✓	✓	✓

6.3 Contributions

The variability of both feed solids concentration and rheological properties were determined. This work contributed to understanding the relationships between the sludge rheological properties with filtrate suspended solids and solids recovery for a belt filter press.

Four correlations describing the relationship between yield stress, viscosity, filtrate suspended solids and solids capture and the belt filter press operating parameters respectively were developed.

The relationship between rheological properties and filtrate suspended solids was established.

The relationship between rheological properties and solids capture was established.

The findings of chapter 4 have been presented at the 6th Southern African Conference on Rheology:

Kholisa B, Fester VG and Haldenwang R. 2016. Variability of rheological properties of secondary sludge feeds to the belt filter press at various wastewater treatment plants in Cape Town. *Proceedings of the 2016 6th Conference of the Southern African Society of Rheology, Pretoria, 19-20 September 2016.*

6.4 Conclusion

Despite the variation in rheological parameters obtained over time for the various BFPs and operations, the parameters collapsed onto a single curve for each measurement position when presented as a function of solids concentration and it can be described by a power law relation.

Sludge flow rate was found to have a significant effect on the yield stress, viscosity, filtrate suspended solids and solids capture, while the effect of belt speed was insignificant. The sludge cake solids was independent of operating parameters and rheological properties as it remained reasonably constant over the process parameters tested.

6.5 Recommendations for further research

Similar trials should be conducted to develop a correlation between rheological properties and solids concentration after polymer addition to feed sludge using an in-line rheometer.

Further research can be conducted on other types of sludges, polymers and different BFP configurations using a similar methodology in this research in order to see whether it would be possible to control polymer dosing based on rheological properties.

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Appendices

Appendix A Bingham parameters

Table A.1: Plant J Bingham parameters

	Yield stress [Pa]				*Viscosity [Pa.s]*			
	Feed	100 cm	200 cm	300 cm	Feed	100 cm	200 cm	300 cm
Week 1	1,17	4,42	11,58	40,52	0,0006	0,0088	0,018	0,0541
Week 2	0,10	25,51	35,42	30,64	0,0032	0,0355	0,046	0,0416
Week 3	0,08	20,04	26,51	29,89	0,0026	0,0288	0,0352	0,0375
Week 4	0,13	2,40	6,30	26,19	0,0029	0,0066	0,0128	0,043
Week 5	0,14	1,23	2,64	8,01	0,0023	0,0046	0,0062	0,0151
Week 6	0,11	12,69	22,00	31,65	0,0014	0,0194	0,0284	0,0387
Week 7	0,06	2,47	21,06	39,98	0,0023	0,007	0,0285	0,0523
Week 8	0,10	5,35	17,76	40,70	0,0012	0,0108	0,0262	0,0577
Week 9	0,24	5,59	19,45	40,76	0,0011	0,01	0,0269	0,0542
Week 10	0,14	40,74	53,79	77,21	0,0011	0,0542	0,0678	0,0969
Week 11	0,01	7,66	20,05	47,29	0,0007	0,0143	0,0295	0,0601
Week 12	0,02	2,91	8,24	7,33	0,0015	0,0069	0,0125	0,0129
Av	0,19	10,92	20,40	35,01	0,00174	0,0172	0,0282	0,0470
STD	0,31	12,07	13,91	18,29	0,00088	0,0151	0,0166	0,0219
CV	164%	111%	68%	52%	50%	87%	59%	47%

Table A.2: Plant K Bingham parameters

	Yield stress [Pa]				*Viscosity [Pa.s]*			
	Feed	100cm	200cm	300cm	Feed	100cm	200cm	300cm
Week 1	16,57	61,86	68,17	103,16	0,0259	0,072	0,080	0,134
Week 2	14,72	93,17	144,15	177,47	0,0260	0,115	0,192	0,252
Week 3	14,88	128,34	188,29	200,94	0,0241	0,341	0,263	0,284
Week 4	15,25	152,70	155,46	227,30	0,0240	0,211	0,214	0,340
Week 5	15,64	160,46	197,29	218,89	0,0251	0,230	0,288	0,324
Week 6	14,80	83,65	83,65	142,53	0,0253	0,113	0,113	0,204
Week 7	13,82	168,78	195,00	205,49	0,0224	0,221	0,265	0,292
Week 8	11,58	125,17	134,16	152,86	0,0211	0,158	0,176	0,194
Week 9	15,07	163,84	181,44	193,19	0,0249	0,203	0,218	0,238
Week 11	13,78	137,58	166,07	162,56	0,0230	0,161	0,197	0,202
Av	14,61	127,55	151,37	178,44	0,0242	0,182	0,201	0,246
STD	1,34	36,92	45,18	38,50	0,0016	0,077	0,066	0,065
CV	9%	29%	30%	22%	7%	42%	33%	26%

Table A.3: Plant M Bingham parameters

	Yield stress [Pa]				*Viscosity [Pa.s]*			
	Feed	100cm	200cm	300cm	Feed	100cm	200cm	300cm
Week 1	1,21	40,08	67,55	96,24	0,0033	0,0834	0,1077	0,206
Week 2	0,93	14,40	18,18	45,66	0,0027	0,0263	0,0329	0,0751
Week 3	0,84	2,30	8,22	9,30	0,0049	0,009	0,3548	0,6834
Week 4	0,73	2,40	17,00	33,55	0,0039	0,0066	0,0371	0,0574
Week 5	0,80	1,14	9,72	14,43	0,0035	0,0054	0,0213	0,0282
Week 6	1,00	1,22	1,01	6,09	0,0037	0,0046	0,0048	0,0139
Week 7	0,79	1,22	3,50	1,28	0,0025	0,0031	0,0072	0,0028
Week 9	0,84	6,04	19,08	22,26	0,0031	0,0136	0,0326	0,0391
Week 10	0,60	3,71	3,14	7,56	0,0037	0,0073	0,0086	0,0154
Week 11	0,81	6,20	15,30	23,86	0,003	0,0163	0,0318	0,0492
Week 12	0,60	3,08	7,37	12,28	0,0033	0,0067	0,0161	0,0236
Av	0,83	7,44	15,46	24,77	0,00342	0,0166	0,0596	0,109
STD	0,17	11,49	18,41	27,07	0,00065	0,0232	0,102	0,199
CV	21%	154%	119%	109%	19%	140%	171%	183%

Table A.4: Plant L Bingham parameters

	Yield stress [Pa]				*Viscosity [Pa.s]*			
	Feed	100cm	200cm	300cm	Feed	100cm	200cm	300cm
Week 1	0,79	0,76	1,74	8,68	0,0018	0,004	0,0041	0,0106
Week 3	0,76	0,71	0,85	2,15	0,003	0,0031	0,0044	0,0063
Week 4	0,13	1,69	2,62	3,19	0,0029	0,0042	0,0059	0,0072
Week 5	1,01	4,48	15,63	7,73	0,0039	0,0094	0,023	0,0132
Week 6	1,10	3,90	7,49	10,70	0,0045	0,0094	0,00141	0,0197
Week 7	1,50	21,51	43,95	63,06	0,0042	0,032	0,0571	0,0785
Week 9	1,14	8,83	19,79	29,05	0,0042	0,0156	0,0293	0,0381
Week 10	1,30	14,48	28,28	67,92	0,0034	0,0239	0,041	0,0878
Week 11	0,74	7,20	36,79	35,39	0,0033	0,0125	0,0467	0,0424
Week 12	0,93	7,65	13,76	31,47	0,0022	0,013	0,0223	0,0438
Av	0,94	7,12	17,09	25,93	0,00334	0,0127	0,0235	0,0348
STD	0,37	6,61	15,12	24,07	0,00089	0,0092	0,0199	0,0292
CV	40%	93%	88%	93%	27%	73%	84%	84%

Appendix B Sludge solids concentration

Table A.5: Plant J solids concentration at different sampling points per week

Week	*Plant J solids concentration [%]*				
	Feed	***Linear screen***			***Cake***
		100cm	***200cm***	***300cm***	
Week 1	0.10	1.30	2.57	3.27	12.87
Week 2	0.03	3.07	3.33	3.40	12.53
Week 3	0.23	0.77	3.57	3.97	14.73
Week 4	0.43	1.17	1.63	3.20	14.63
Week 5	0.43	0.60	1.00	2.20	13.57
Week 6	0.10	2.37	3.17	3.47	14.60
Week 7	1.00	1.27	2.93	3.99	14.33
Week 8	0.10	1.83	3.50	4.30	12.33
Week 9	0.17	1.60	2.97	4.10	12.97
Week 10	0.20	2.90	3.23	4.00	13.17
Week 11	0.10	2.13	3.17	4.10	14.37
Week 12	0.20	0.93	2.17	2.30	13.83
Average	0.26	1.66	2.77	3.53	13.58
SD	±0.27	±0.81	±0.79	±0.70	±0.93
CV	±103%	±49%	±29%	±20%	±7%

Table A.6: Plant K solids concentration at different sampling points per week

	Plant K solids concentration [%]				
	Feed	***Linear screen***			***Cake***
		100cm	***200cm***	***300cm***	
Week 1	2.47	4.17	4.90	5.10	12.03
Week 2	2.47	5.00	5.60	6.17	14.27
Week 3	2.50	6.27	6.30	6.73	14.43
Week 4	2.73	6.17	6.87	7.97	12.73
Week 5	2.57	6.13	6.67	7.13	13.33
Week 6	2.57	4.83	5.67	5.77	12.57
Week 7	2.40	6.30	6.67	7.07	13.37
Week 8	2.23	6.43	6.53	6.60	14.10
Week 9	2.37	6.77	6.87	6.97	14.27
Week 11	2.30	6.30	6.70	7.43	14.37
Average	2.46	5.84	6.28	6.69	13.55
SD	±0.14	±0.85	±0.66	±0.83	±0.87
CV	±6%	±15%	±11%	±12%	±6%

Table A.7: Plant L solids concentration at different sampling points per week

Week	*Plant L solids concentration [%]*				
	Feed	***Linear screen***			***Cake***
		100cm	***200cm***	***300cm***	
Week 1	0.27	0.23	0.77	1.33	10.20
Week 3	0.33	0.57	0.77	0.90	14.43
Week 4	0.50	0.57	0.70	0.77	13.17
Week 5	0.50	1.10	1.30	1.87	12.50
Week 6	0.70	1.10	1.33	1.90	10.43
Week 7	0.80	3.00	3.47	3.63	10.77
Week 9	0.63	2.00	3.00	3.10	10.90
Week 10	0.63	2.00	3.20	3.73	11.43
Week 11	0.50	2.00	2.77	3.47	12.47
Week 12	0.43	1.53	2.07	3.30	12.93
Average	0.53	1.41	1.94	2.40	11.92
SD	±0.16	±0.86	±1.10	±1.17	±1.39
CV	±31%	±61%	±57%	±49%	±12%

Table A.8: Plant M solids concentration at different sampling points per week

Week	*Plant M solids concentration [%]*				
	Feed	***Linear screen***			***Cake***
		100cm	***200cm***	***300cm***	
Week 1	0.53	4.67	5.73	6.57	16.90
Week 2	0.93	3.83	4.37	5.97	17.13
Week 3	0.70	1.83	3.00	4.23	14.87
Week 4	0.80	2.77	4.00	5.43	14.37
Week 5	0.60	1.10	2.80	3.47	13.03
Week 6	0.63	0.80	1.17	2.10	14.43
Week 7	0.60	1.03	1.07	1.90	12.40
Week 9	0.67	2.63	4.00	4.50	12.63
Week 10	0.83	2.20	2.13	2.87	13.37
Week 11	1.00	2.87	4.27	5.00	14.67
Week 12	0.87	1.57	2.33	3.00	12.73
Average	0.74	2.30	3.17	4.09	14.23
SD	±0.15	±1.21	±1.45	±1.56	±1.63
CV	±21%	±53%	±46%	±38%	±11%

Appendix C Wastewater treatment plants process flow charts

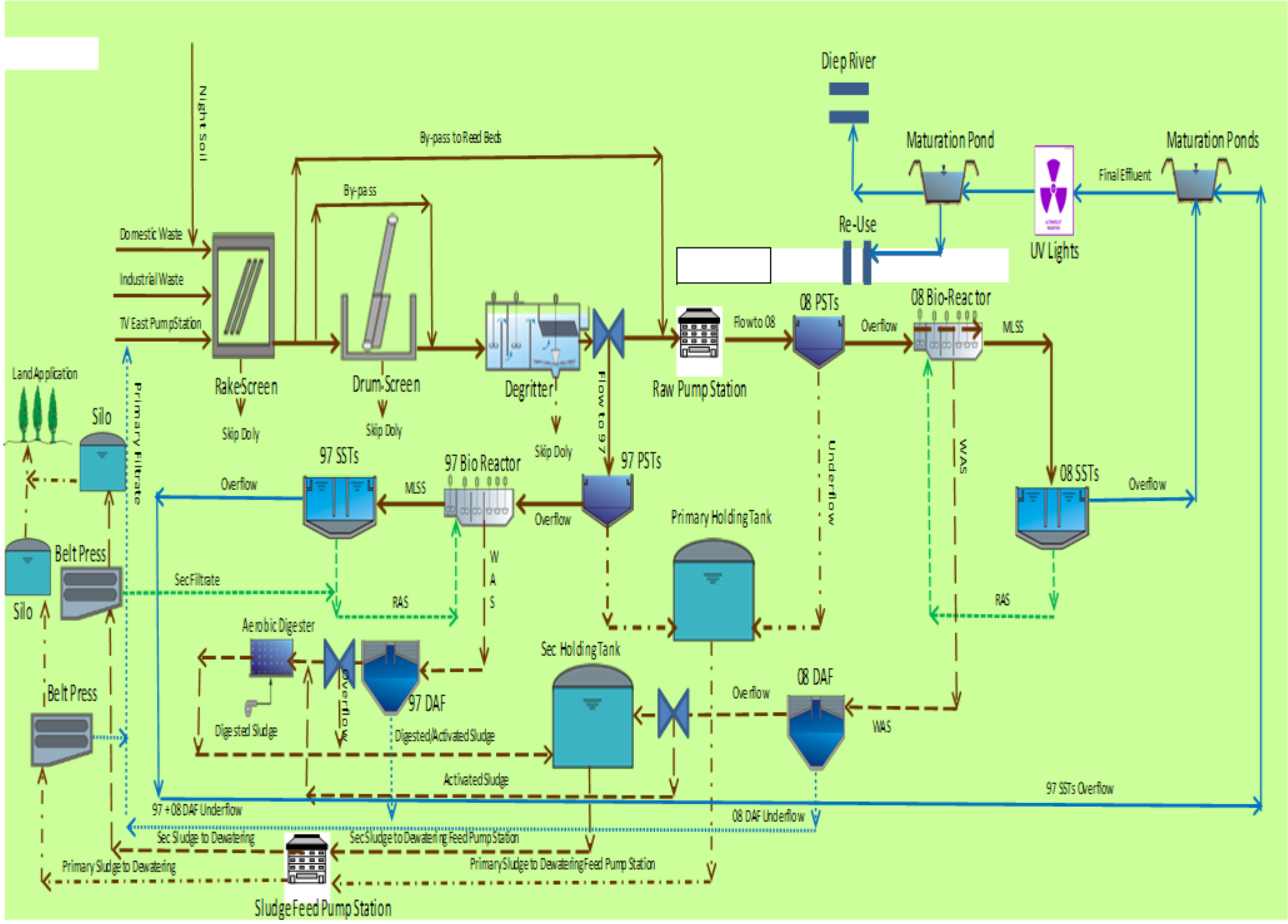

Figure A.1 Plant K WWTP process flow chart

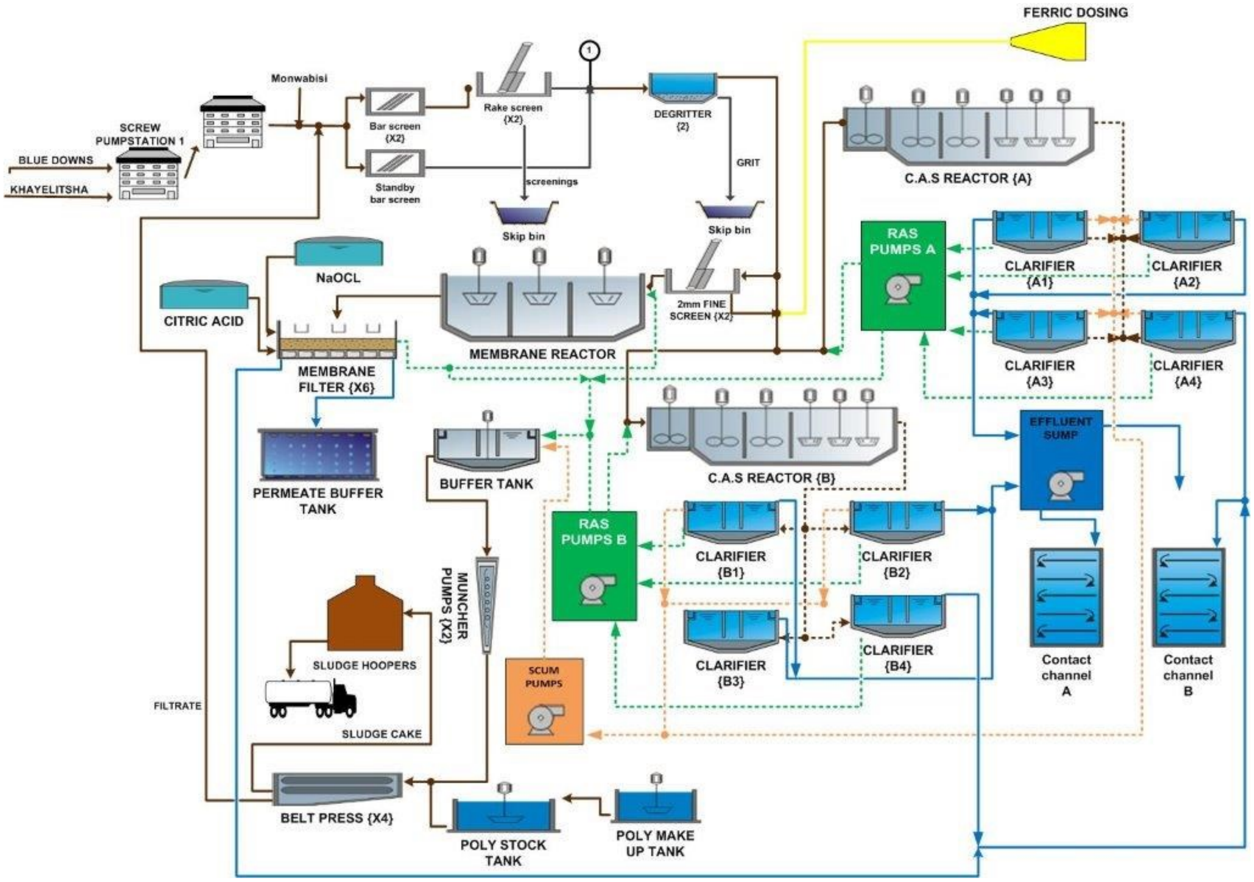

Figure A.2 Plant M WWTP process flow chart

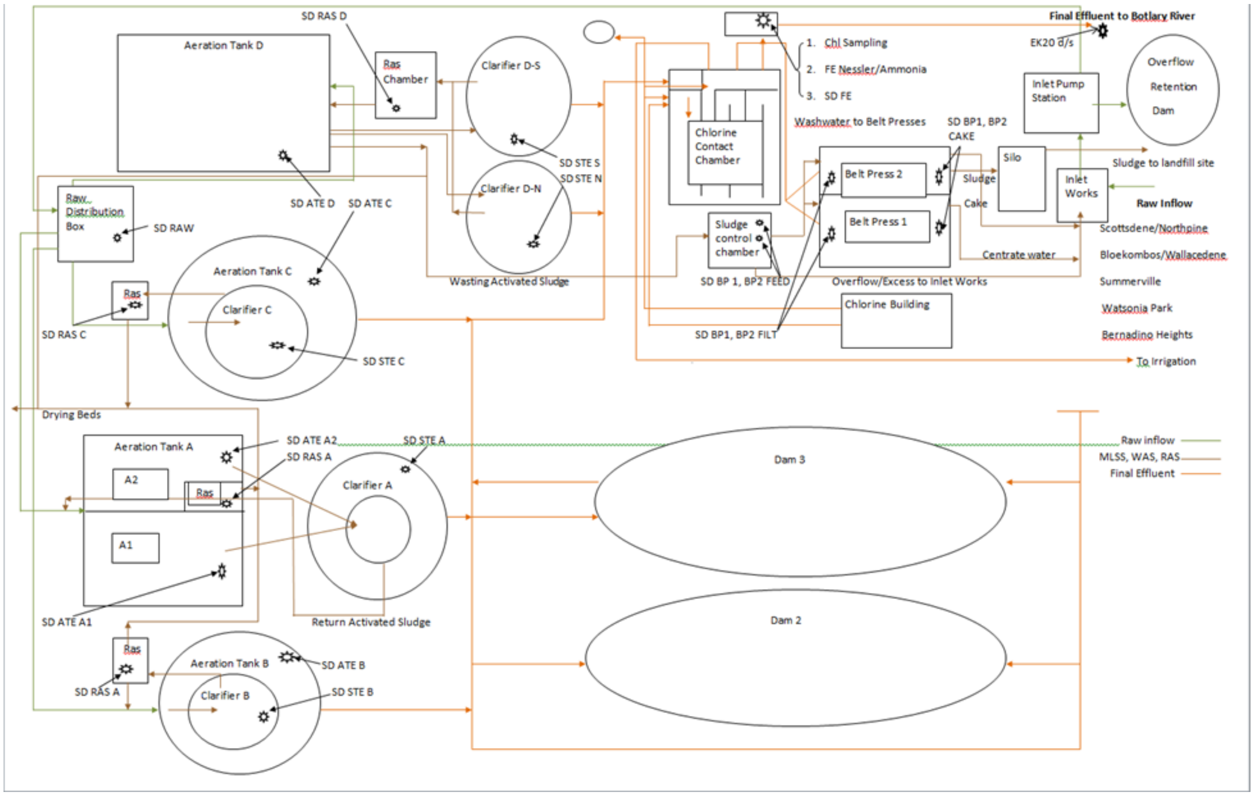

Figure A.3 Plant L WWTP process flow chart

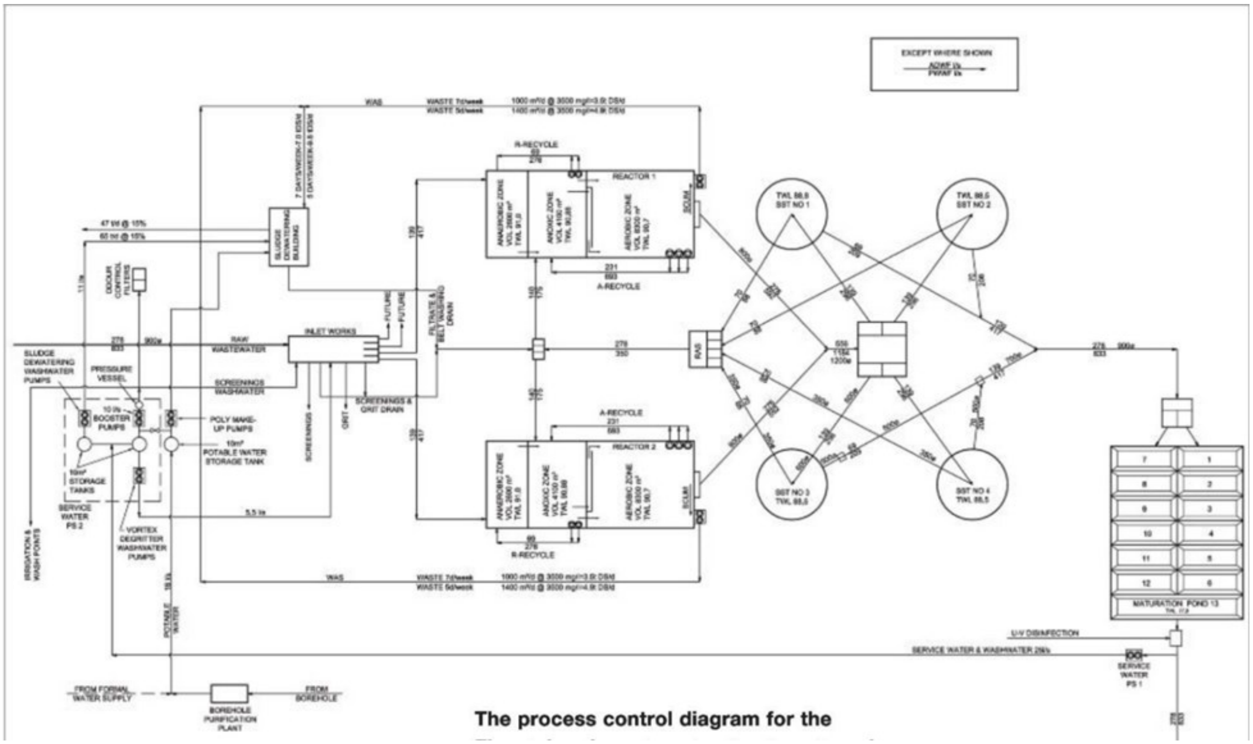

Figure A.4 Plant J WWTP process flow chart